Climate and Community Codes

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Climate Model Basics

An old saying….
"Climate is what you expect, weather is what you get"

- Climate is the *average* of weather.

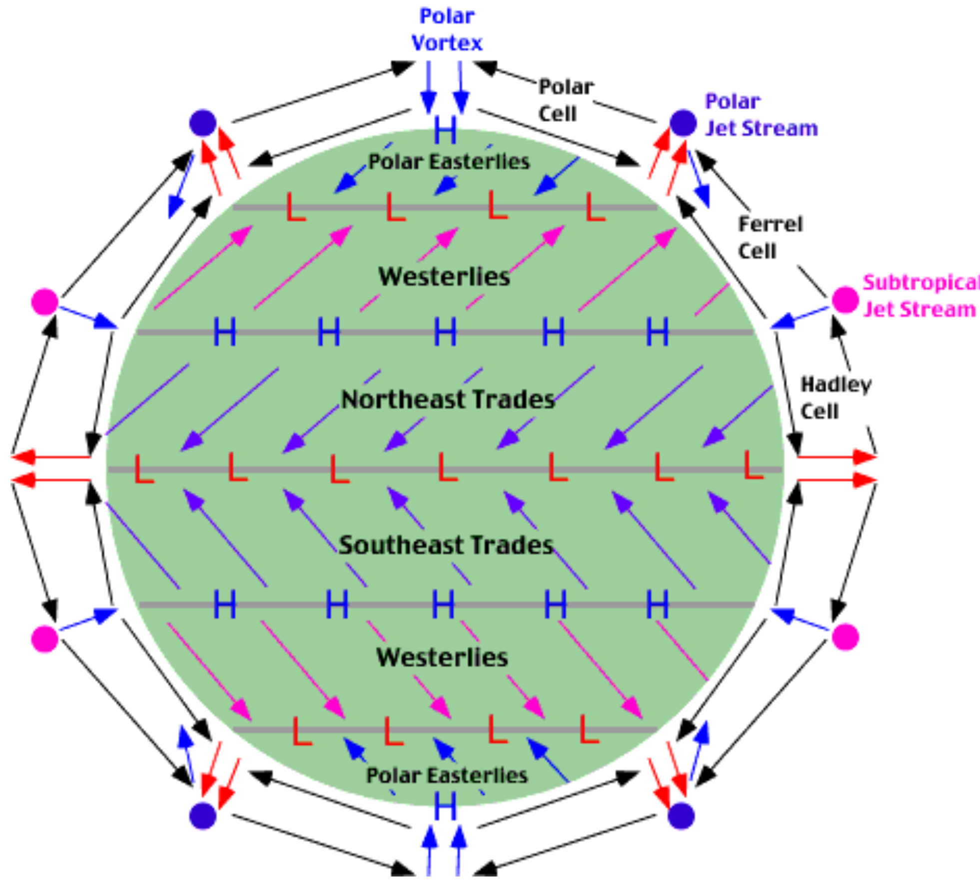
- The average high temperature for today is calculated by taking the average of several (usually 30) Aug 13th highs.

$$\frac{(T\ \text{Aug}13^{th}\ ,\ 1981) + (T\ \text{Aug}13^{th}\ ,\ 1982) + \ldots + (T\ \text{Aug}\ 13^{th}\ ,\ 2010)}{30}$$

From NWS site: "Please note, as of forecast May 2011, the climatological reference period has been updated from 1971-2000 to 1981-2010"

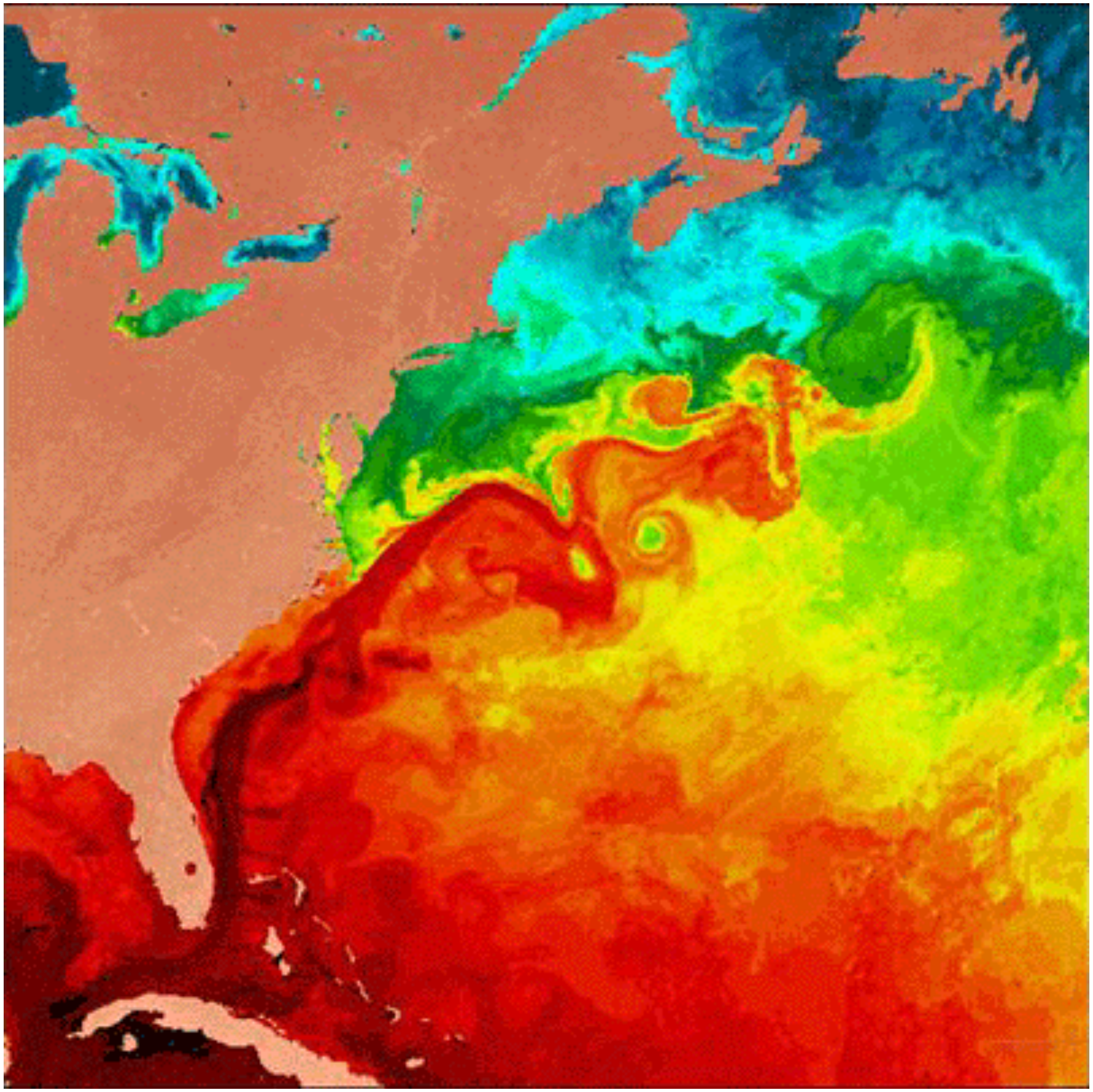
To model the climate system, must model years of global weather

Need to simulate weather-scale phenomena over the entire globe.

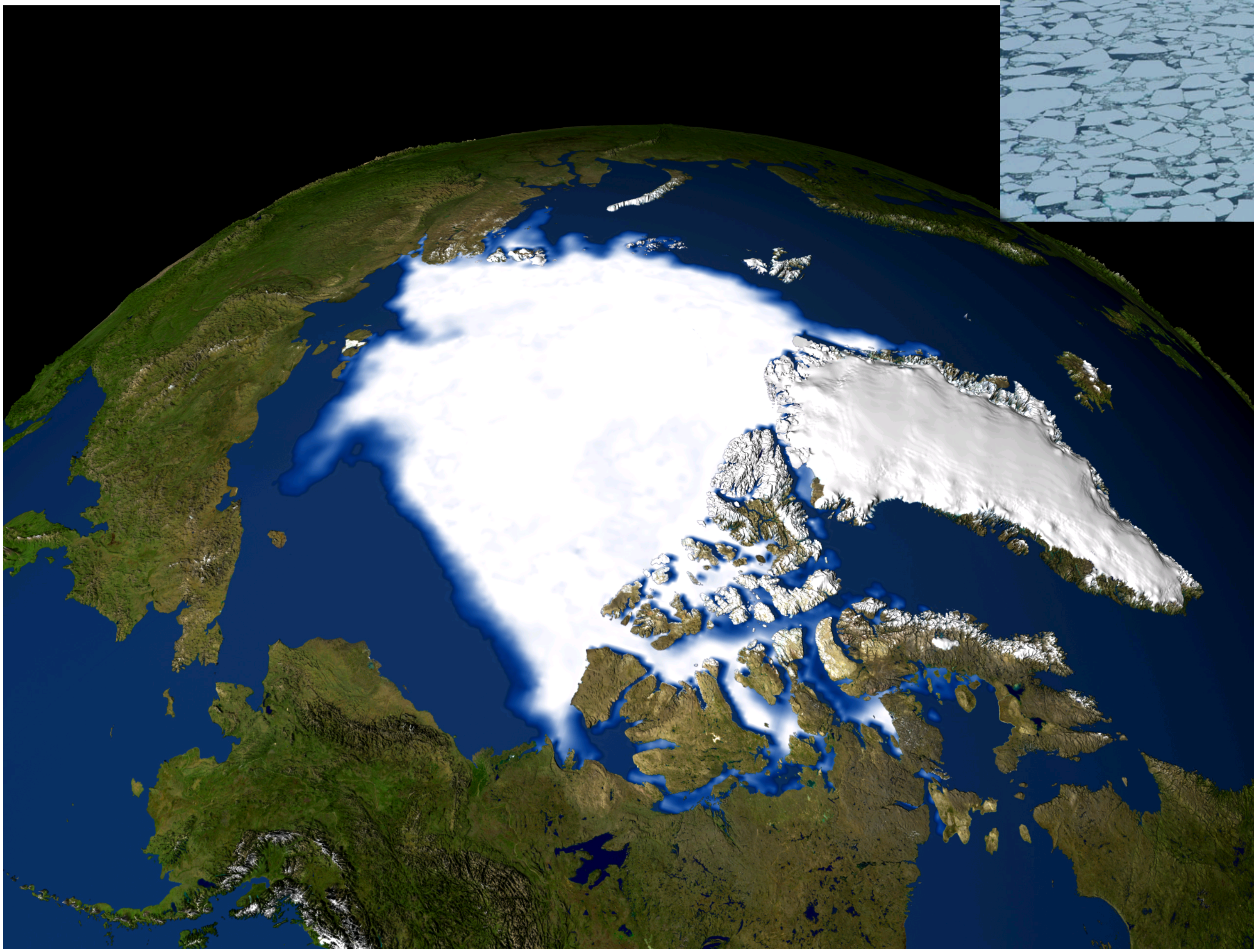


Weather is embedded in the *general circulation* of the atmosphere

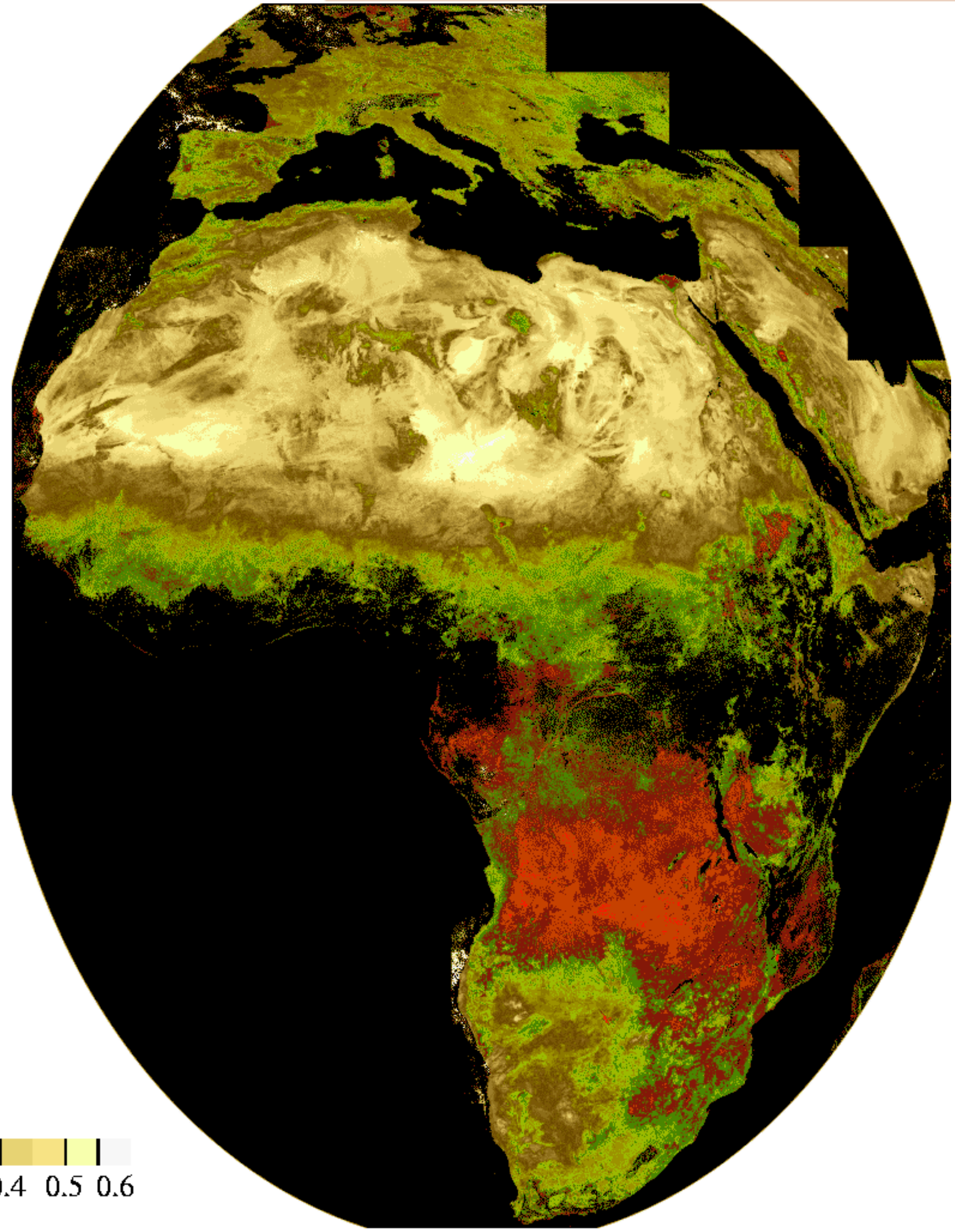
The ocean also plays a role in determining the global climate



As does Sea Ice….

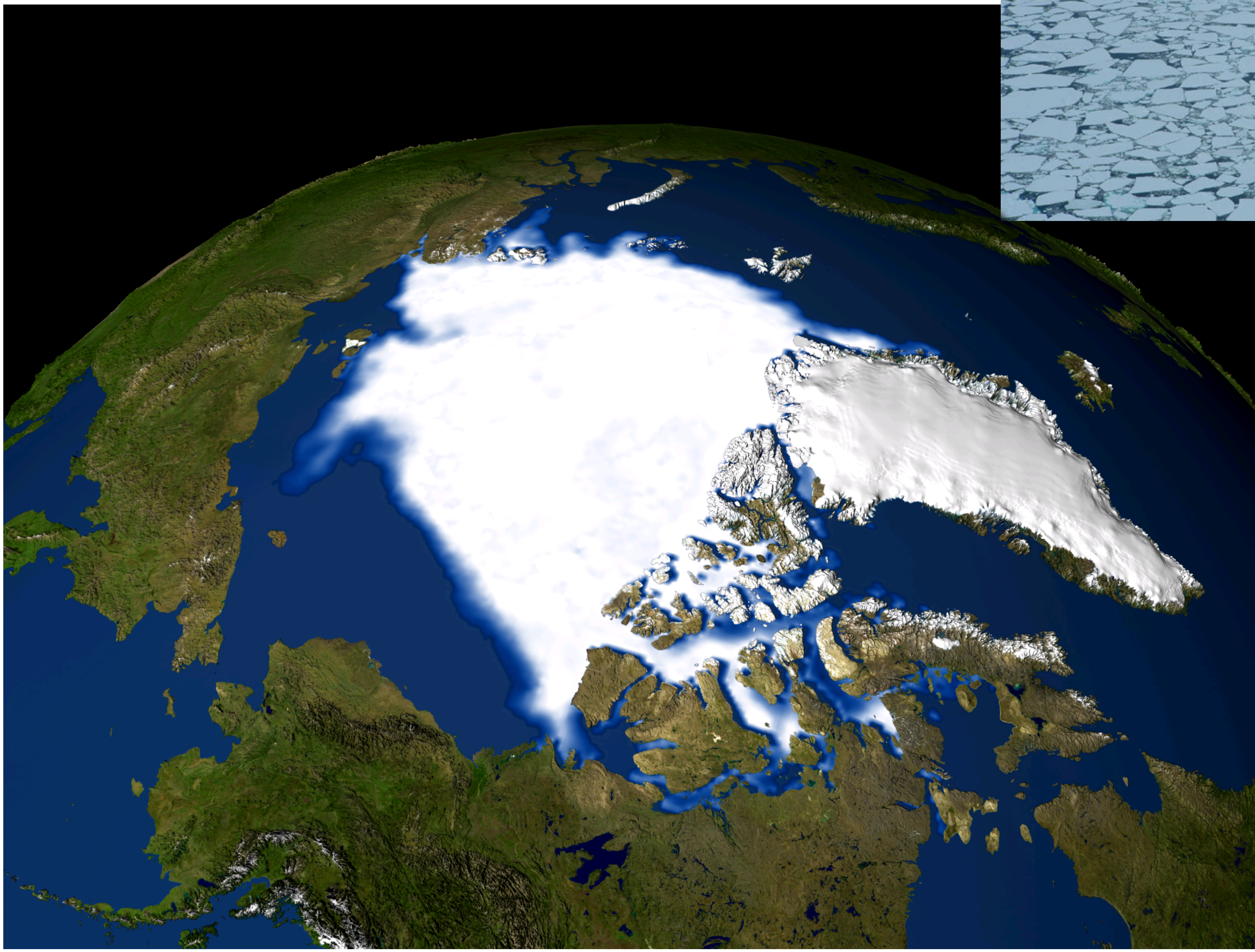


And the land surface



Amount of sunlight reflected

As does Sea Ice....



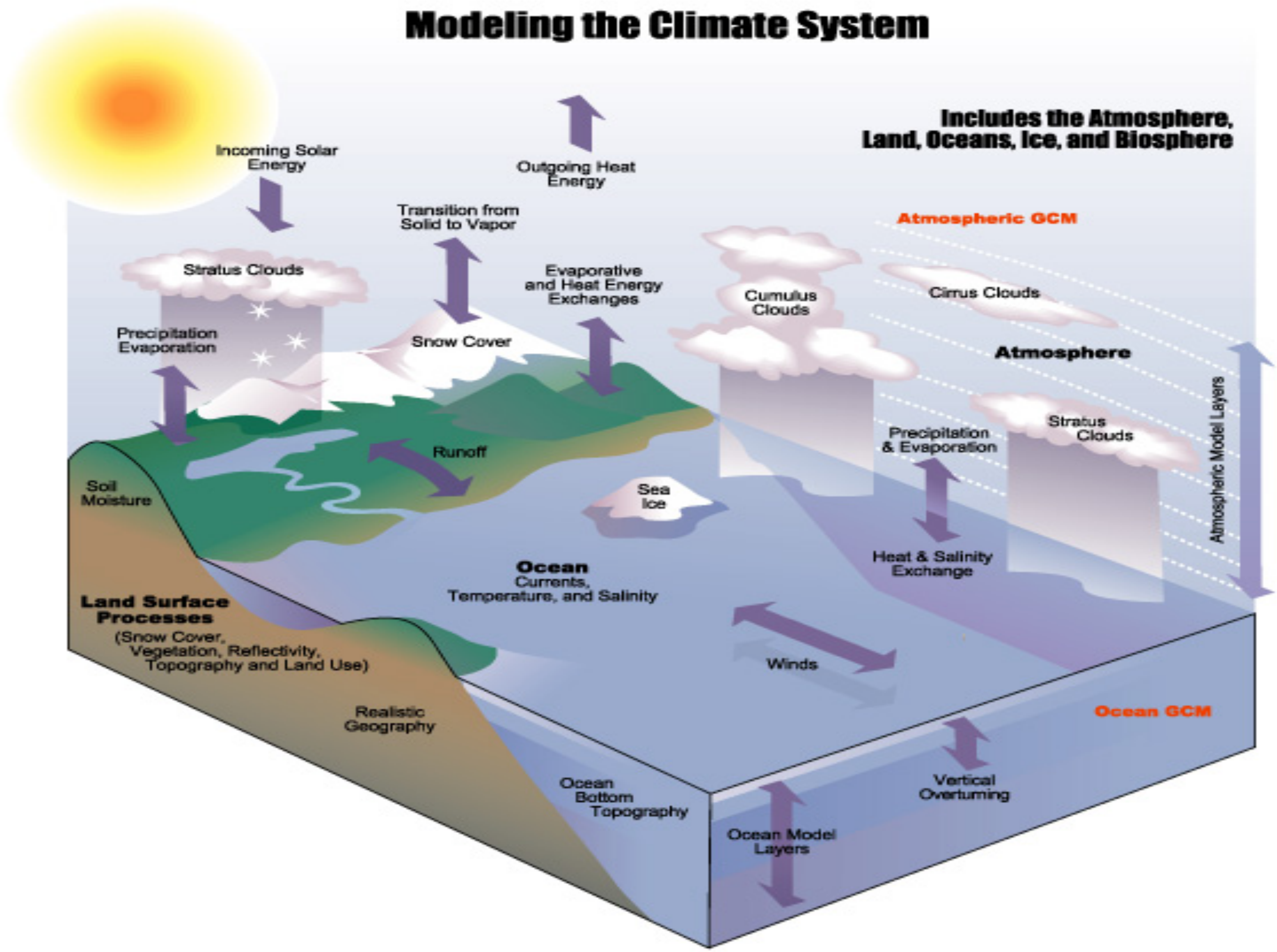


Figure: U.S. Global Change Research Program

GCM: General Circulation Model

- Solves the "primitive equations", a set of non-linear PDEs which ultimately derive from the Navier-Stokes equations.

- Fundamental properties of geophysical fluids:
  - Fluid is rotating
  - Fluid is on a sphere
  - Fluid is acted upon by gravity

- Assumptions:
  - Thin Stratified Fluid
  - Hydrostatic
  - Anelastic and Boussinesq (no sound waves, small aspect ratio, motions are shallow)

- Derived in a non-inertial reference frame rotating with the Earth

The "Primitive equations" in spherical coordinates

momentum equations:

Coriolis force

$$\frac{\partial}{\partial t}u + \mathcal{L}(u) - (uv\tan\phi)/a - fv = -\frac{1}{\rho_0 a\cos\phi}\frac{\partial p}{\partial \lambda} + \mathcal{F}_{Hx}(u,v) + \mathcal{F}_V(u)$$

$$\frac{\partial}{\partial t}v + \mathcal{L}(v) + (u^2\tan\phi)/a + fu = -\frac{1}{\rho_0 a}\frac{\partial p}{\partial \phi} + \mathcal{F}_{Hy}(u,v) + \mathcal{F}_V(v)$$

Advection

$$\mathcal{L}(\alpha) = \frac{1}{a\cos\phi}\left[\frac{\partial}{\partial\lambda}(u\alpha) + \frac{\partial}{\partial\phi}(\cos\phi\, v\alpha)\right] + \frac{\partial}{\partial z}(w\alpha)$$

Horizontal Friction

$$\mathcal{F}_{Hx}(u,v) = A_M\left\{\nabla^2 u + u(1-\tan^2\phi)/a^2 - \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial v}{\partial\lambda}\right\}$$

$$\mathcal{F}_{Hy}(u,v) = A_M\left\{\nabla^2 v + v(1-\tan^2\phi)/a^2 + \frac{2\sin\phi}{a^2\cos^2\phi}\frac{\partial u}{\partial\lambda}\right\}$$

$$\nabla^2\alpha = \frac{1}{a^2\cos^2\phi}\frac{\partial^2\alpha}{\partial\lambda^2} + \frac{1}{a^2\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\frac{\partial\alpha}{\partial\phi}\right)$$

Vertical Friction

$$\mathcal{F}_V(\alpha) = \frac{\partial}{\partial z}\mu\frac{\partial}{\partial z}\alpha$$

The “Primitive equations” continued

continuity equation:

$$\mathcal{L}(1) = 0$$

hydrostatic equation:

$$\frac{\partial p}{\partial z} = -\rho g$$

equation of state:

$$\rho = \rho(\Theta, S, p) \;\rightarrow\; \rho(\Theta, S, z)$$ **(Ocean)**

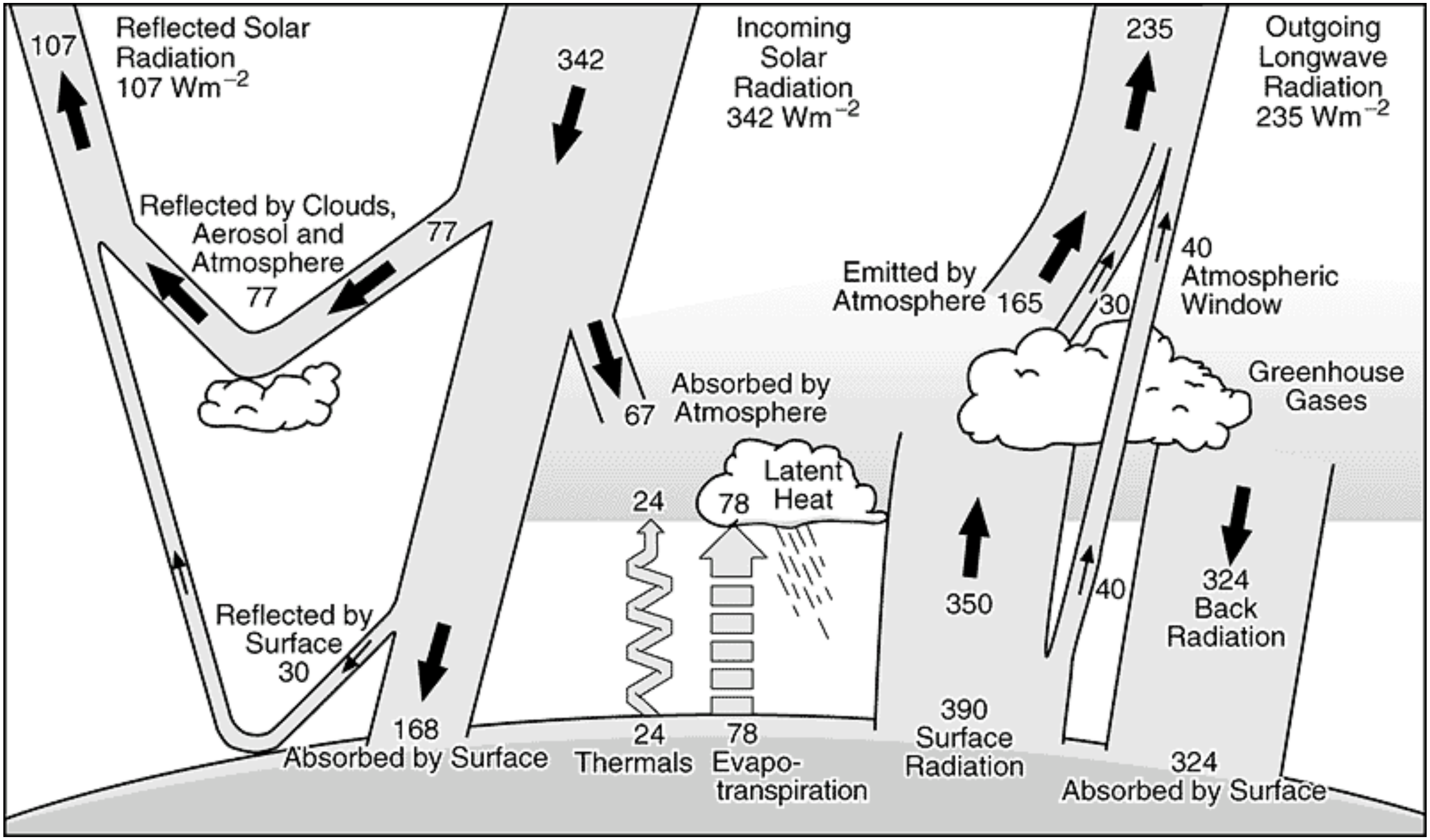
tracer transport:

$$\frac{\partial}{\partial t}\varphi + \mathcal{L}(\varphi) = \mathcal{D}_H(\varphi) + \mathcal{D}_V(\varphi)$$ **+ F(t,u,v,phi)**

$$\mathcal{D}_H(\varphi) = A_H \nabla^2 \varphi$$

$$\mathcal{D}_V(\varphi) = \frac{\partial}{\partial z}\kappa\frac{\partial}{\partial z}\varphi \ ,$$

Heat forcing on the atmosphere: Radiation and other. F(t,u,v,phi)

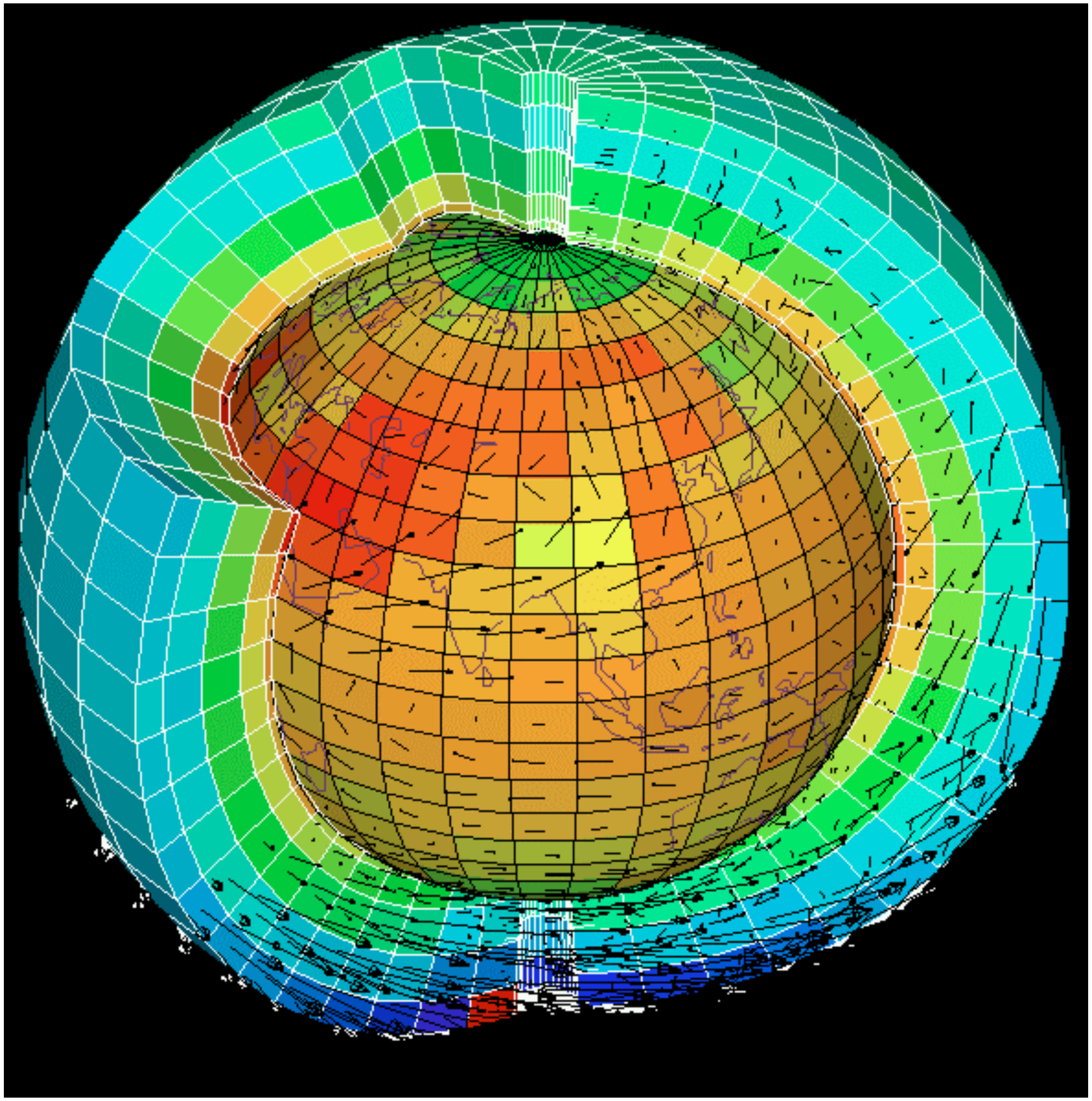


Longwave radiative flux in the 500-1500 cm^{-1} band.

$$
\begin{aligned}
\int_{500}^{1500} (1-\mathcal{T}_\nu)F(B_\nu)d\nu = & \int_{500}^{750} (1-\mathcal{T}^1_{CO_2}\mathcal{T}^1_{N_2O}\mathcal{T}_{H_2O}\mathcal{T}^1_{H_2SO_4})F(B_\nu)d\nu \\
& + \int_{750}^{820} (1-\mathcal{T}^1_{CFC11}\mathcal{T}_{H_2O}\mathcal{T}^*_{H_2SO_4})F(B_\nu)d\nu \\
& + \int_{820}^{880} (1-\mathcal{T}^2_{CFC11}\mathcal{T}_{H_2O}\mathcal{T}^3_{H_2SO_4})F(B_\nu)d\nu \\
& + \int_{880}^{900} (1-\mathcal{T}^1_{CFC12}\mathcal{T}_{H_2O}\mathcal{T}^3_{H_2SO_4})F(B_\nu)d\nu \\
& + \int_{900}^{1000} (1-\mathcal{T}^2_{CO_2}\mathcal{T}_{H_2O}\mathcal{T}^3_{H_2SO_4}\mathcal{T}^3_{CFC11}\mathcal{T}^2_{CFC12})F(B_\nu)d\nu \\
& + \int_{1000}^{1120} (1-\mathcal{T}^3_{CO_2}\mathcal{T}_{O_3}\mathcal{T}_{H_2O}\mathcal{T}^4_{H_2SO_4}\mathcal{T}^4_{CFC11}\mathcal{T}^3_{CFC12})F(B_\nu)d\nu \\
& + \int_{1120}^{1170} (1-\mathcal{T}^4_{CFC12}\mathcal{T}_{H_2O}\mathcal{T}^4_{H_2SO_4}\mathcal{T}^2_{N_2O})F(B_\nu)d\nu \\
& + \int_{1170}^{1500} (1-\mathcal{T}_{CH_4}\mathcal{T}^3_{N_2O}\mathcal{T}_{H_2O}\mathcal{T}^5_{H_2SO_4})F(B_\nu)d\nu
\end{aligned}
$$

F(B) : Plank function for emissivity
T: atmospheric transmission

Equations for the climate system must be solved numerically



Atmospheric General Circulation Model

- Algorithms to solve the primitive equations called "the dynamics"; "dynamical core" "dycore"
- Forcing terms: **F(t,u,v,phi)**
    - *Change in temperature due to radiative transfer*
    - *Effect of clouds on radiative transfer*
    - *Change in moisture due to cloud, rain formation*
    - *Change in temperature due to sensible heat transport through the boundary layer*
    - *Change in temperature due to release of latent heat*
    - *Change in momentum due to friction with surface.*
  - Algorithms for the above called "the physics" or "column physics".
  - Major groupings: longwave radiation, shortwave radiation, boundary layer, deep convection, cloud fraction, gravity wave drag.
  - ***Can take as much or more computer time as the dynamics and also dominate the source code.***

Atmosphere Dynamics Example: The Spectral Transform method:

$$\xi(\lambda, \mu) = \sum_{m=-M}^{M} \sum_{n=|m|}^{N(m)} \xi_n^m P_n^m(\mu) e^{im\lambda}$$

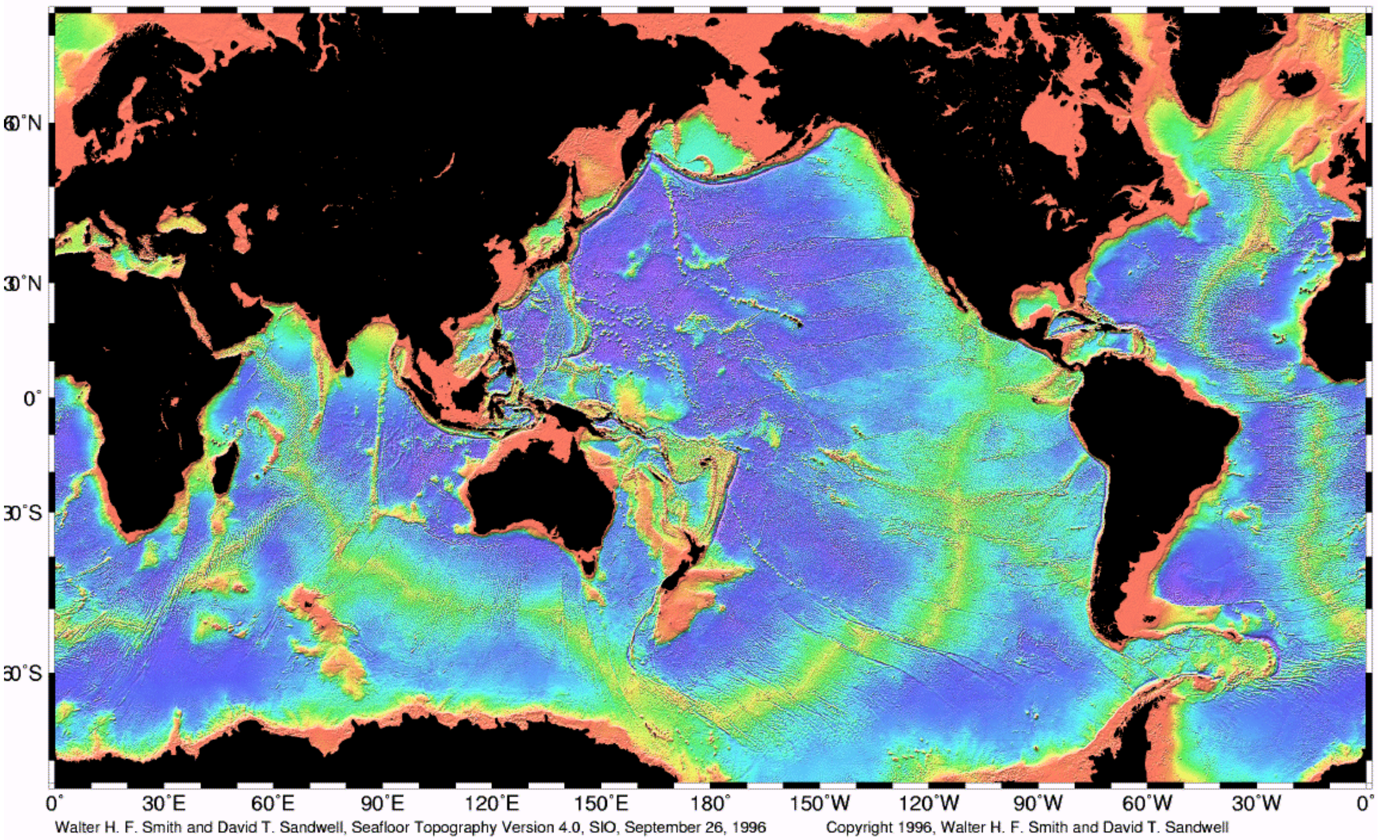
- State variable ξ is represented by a truncated series of spherical harmonic functions.
  - P: associated Legendre function
  - λ: longitude
  - μ: latitude
- **Over 30 years old and still widely used.**
- *aka: Galerkin method with spherical harmonic basis functions.*

Other Numerical methods for Atmospheric GCM's

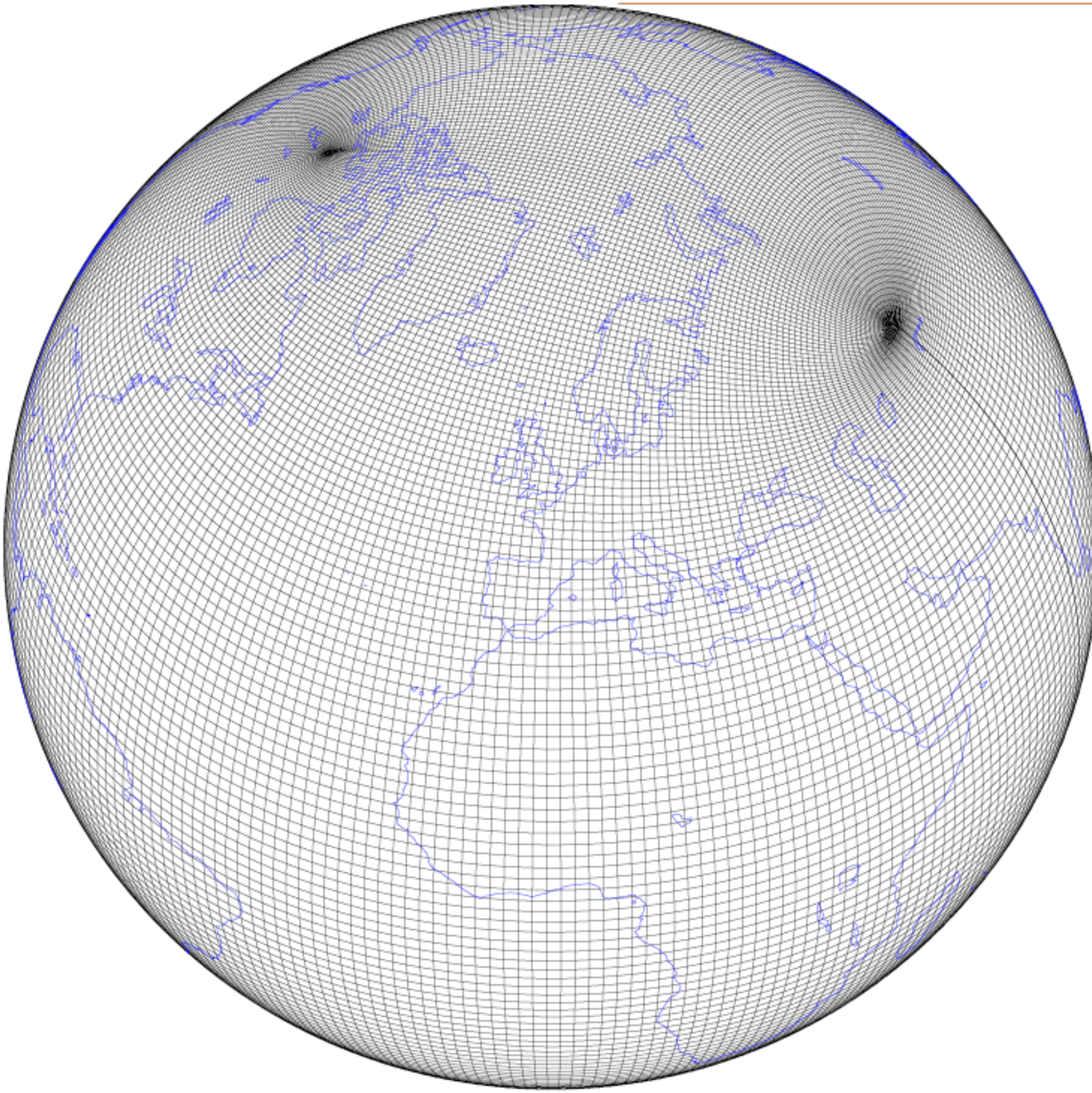
- Finite Volume (FV)
  - Temporarily succeed the spectral method
  - Currently on a lat-lon grid; moving toward "cubed sphere"

- Finite element
  - Just now gaining wide usage.
  - Showing good scalability and performance.

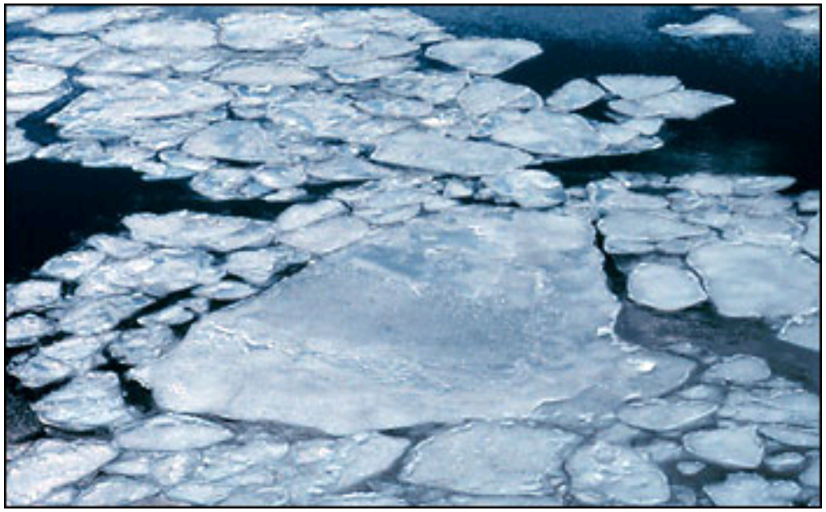
Ocean General Circulation Model



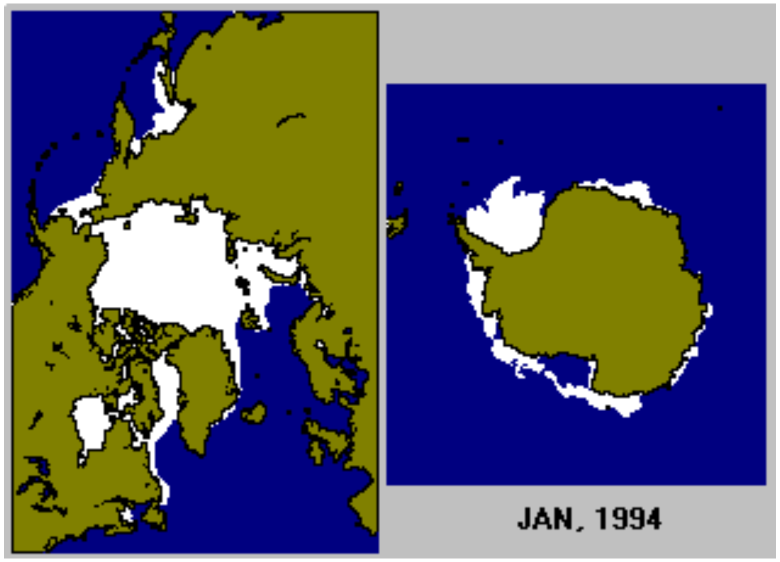
- Very Similar to AGCM except:
  - Presence of side boundaries. Nearly all OGCM's are FD with z-coordinates.
  - Not as much "physics"
  - Motions are slower. Length scales are shorter.
  - Much higher heat capacity. The memory of the climate system is in the ocean.

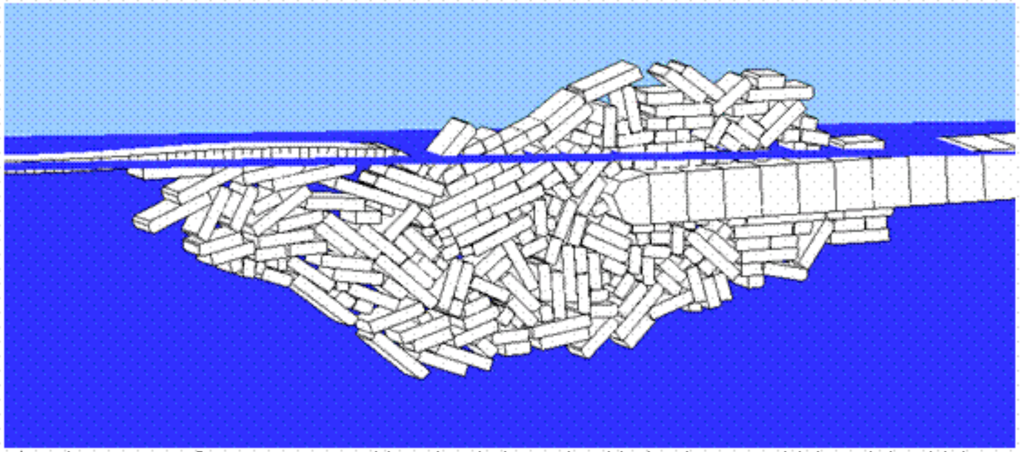


Sea Ice Models



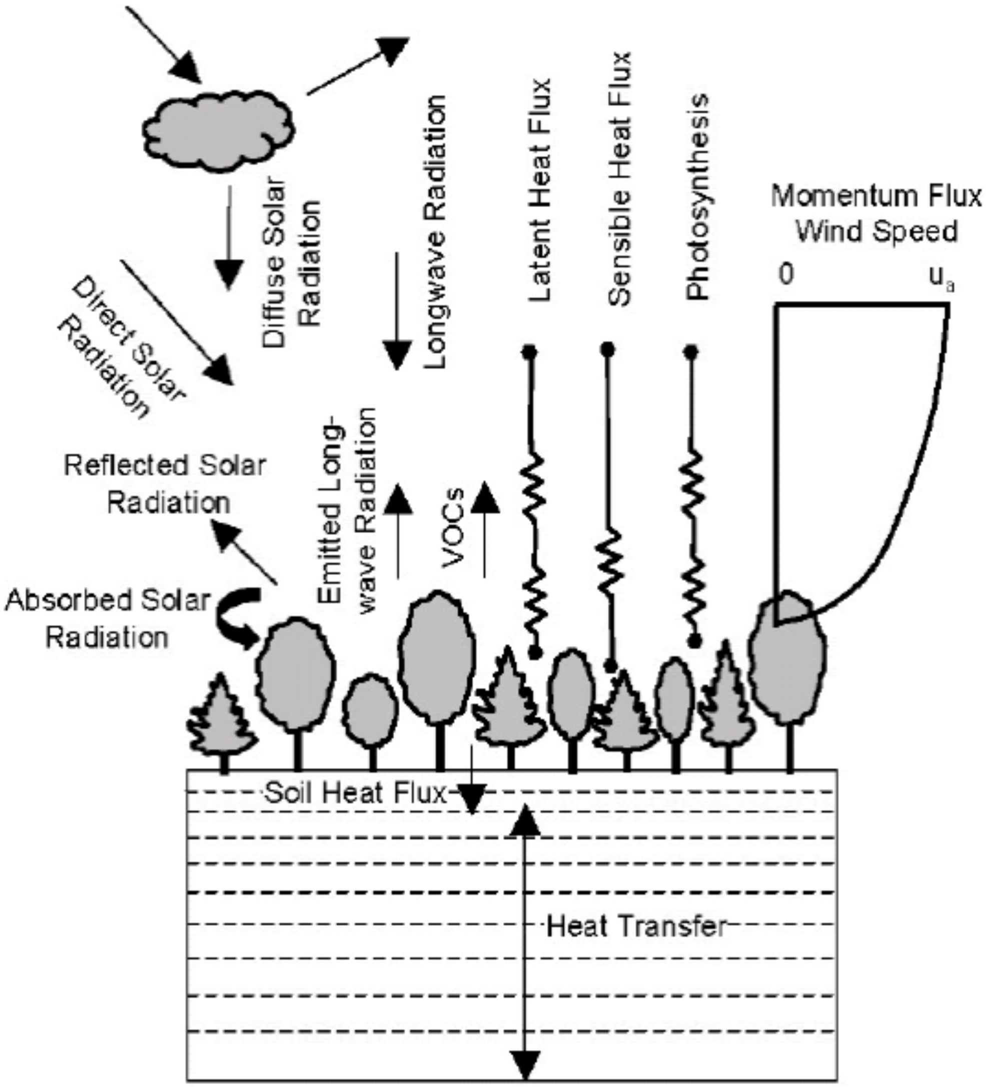
- Thermodynamics: formation, growth, melting, **albedo**, melt ponds.
- Dynamics: transport, internal stress, ridging





Showing a scene from a pressure ridge simulation. The thin ice is 0.5 m thick and the thick floe is 2 m thick.

Land Surface Models



- Nearly all "physics":
  - Vegetation composition, structure
  - Vertical heat transfer in soil.
  - Heat, radiation transfer between ground, canopy and free atmosphere
  - Hydrology of canopy, snow, soil moisture
  - River runoff
- Historically, was part of column physics in the atmosphere model.

Figure: Bonan, NCAR

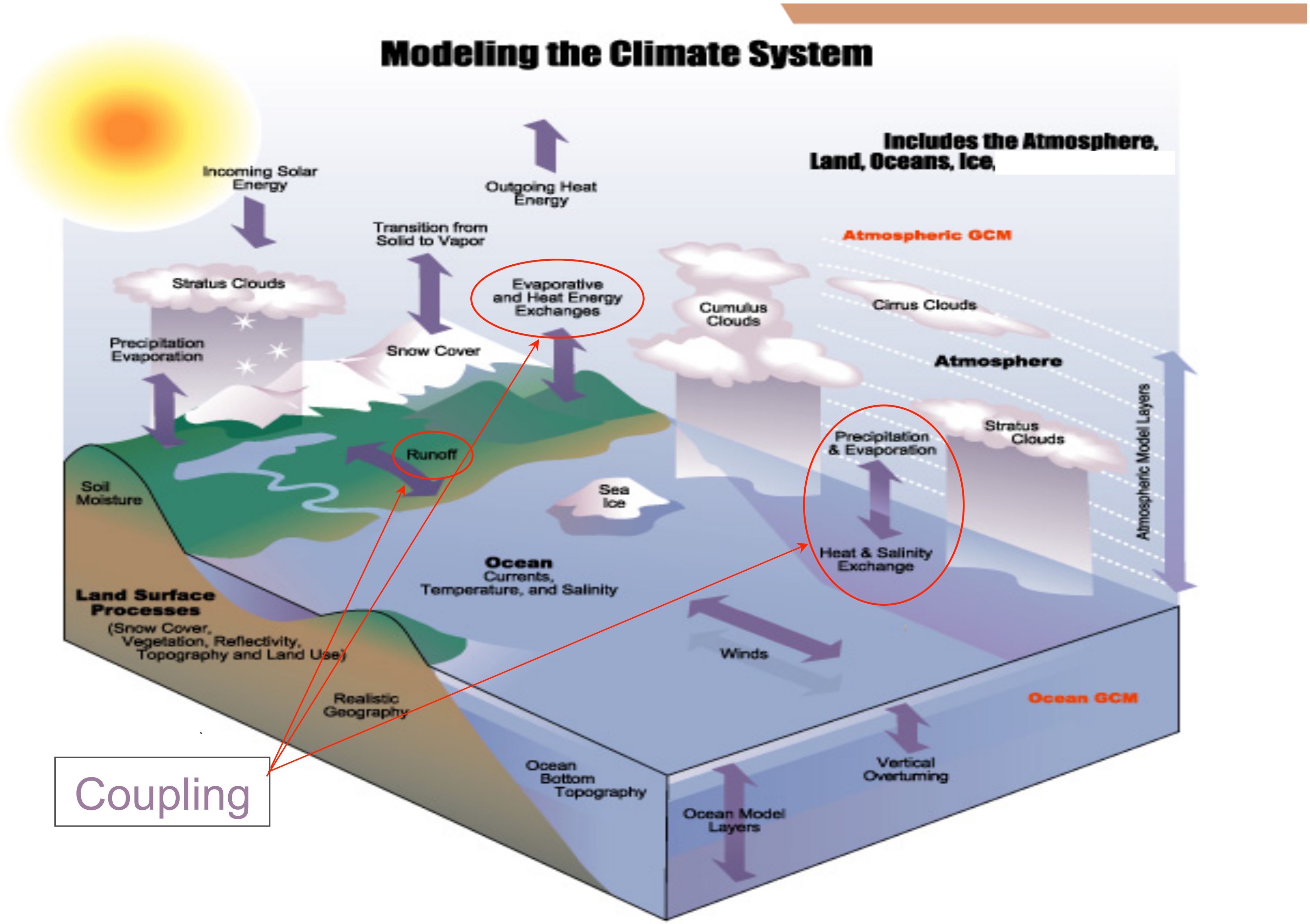
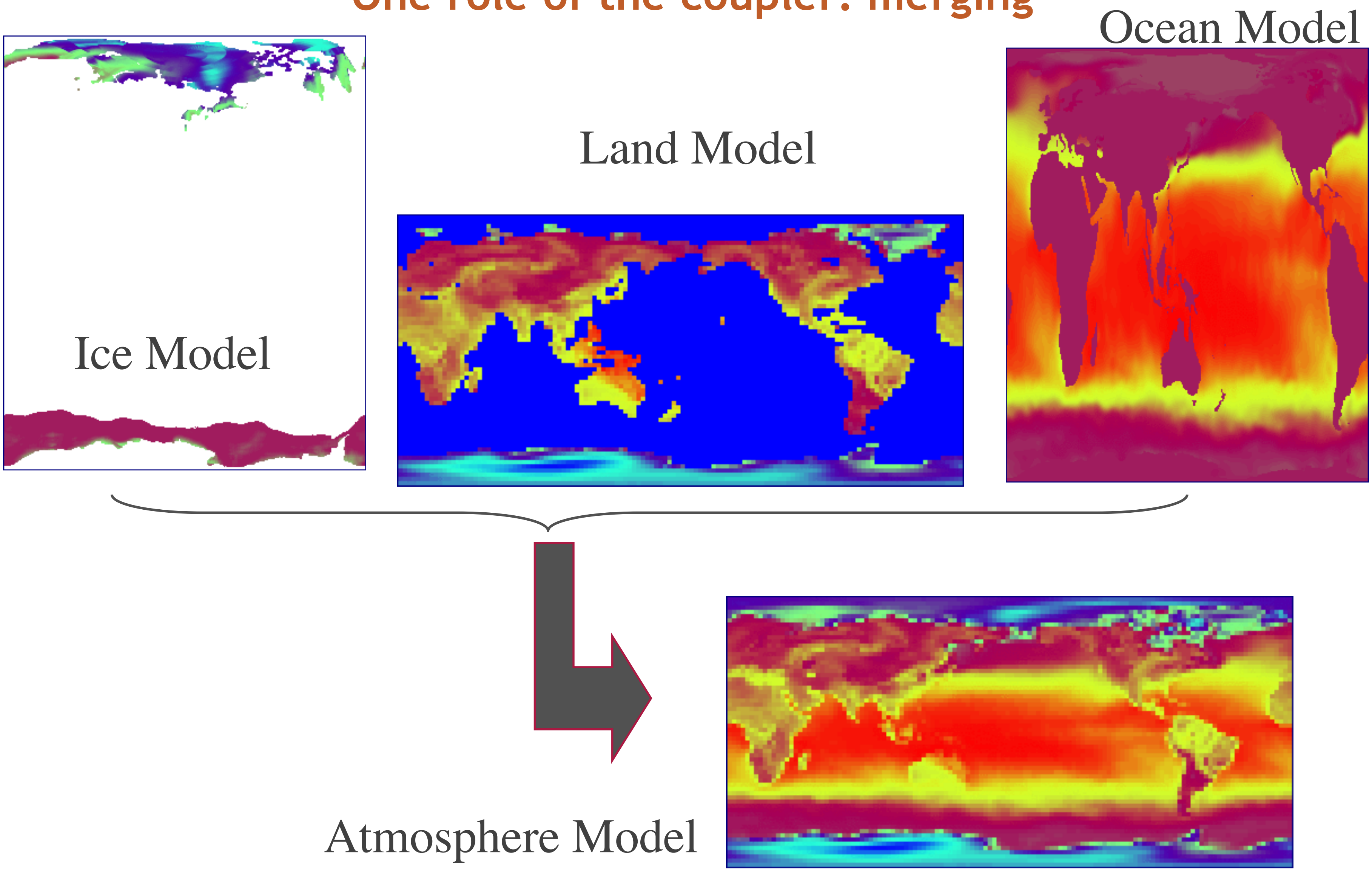


Figure: U.S. Global Change Research Program

One role of the coupler: merging



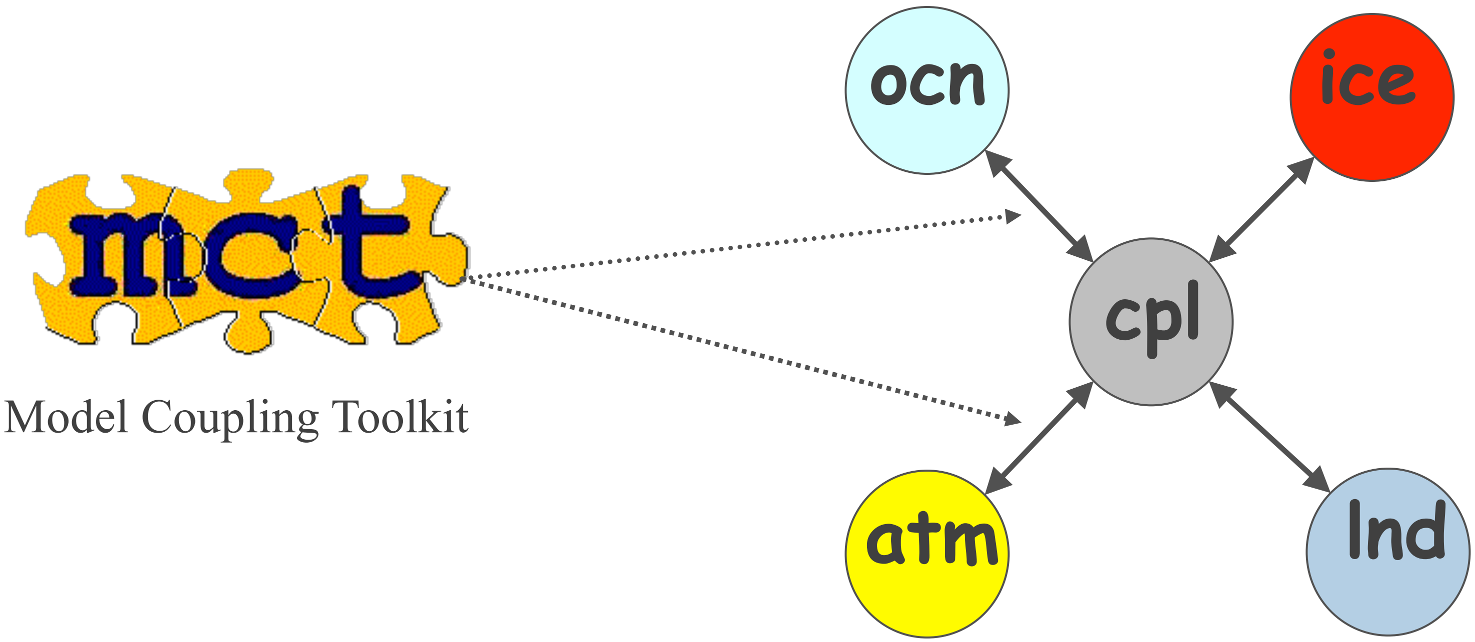
How the climate community builds a coupled model

Building a Coupled Climate Model:

- Coupled Climate Models are almost never written from scratch. Use existing Atmosphere, Ocean models.

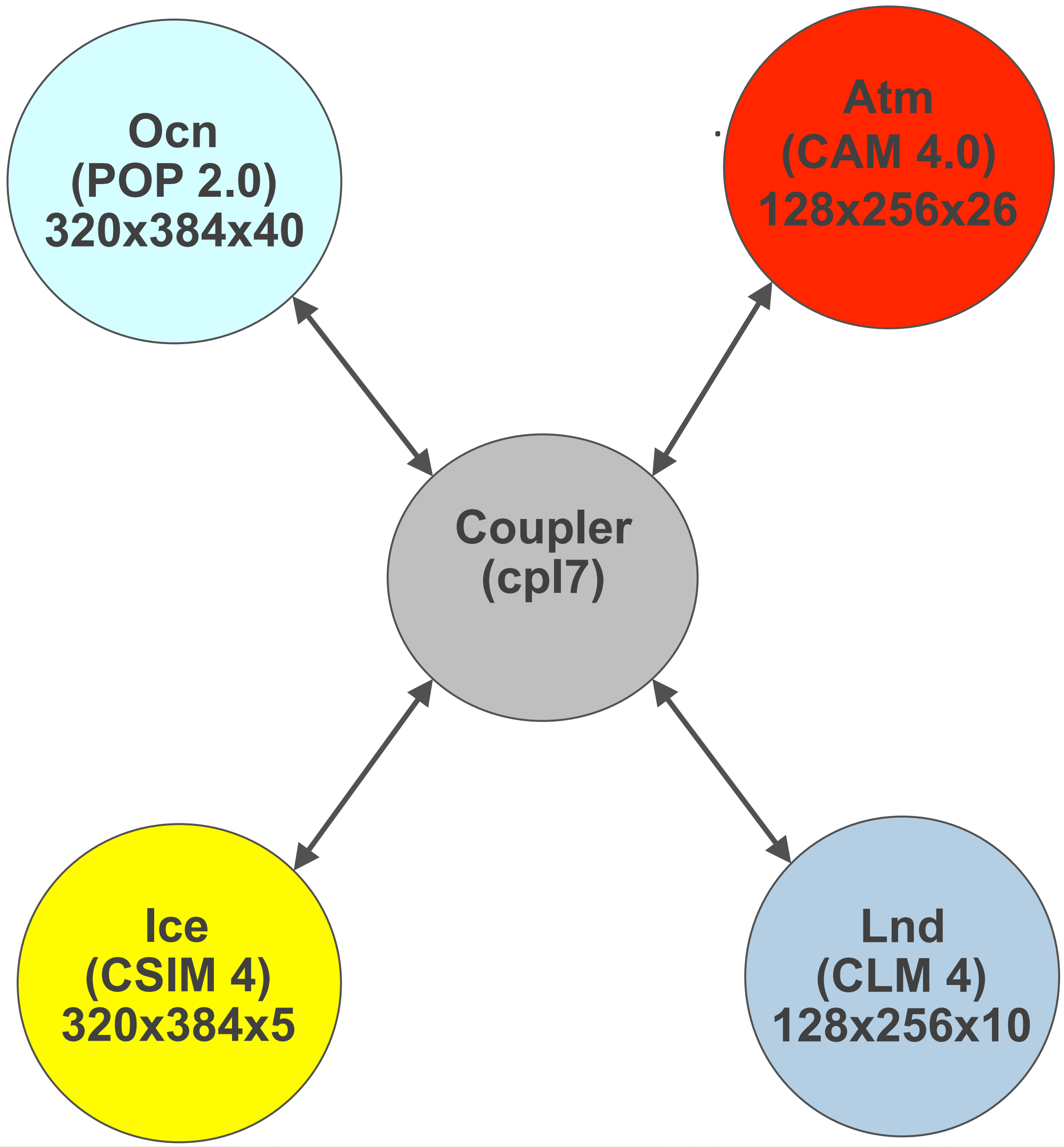
- Source code for each component (Atmosphere, Ocean) developed separately as a standalone model.
  - Source has different coding styles, conventions.
  - Different internal data structures (for holding computed quantities like temperature.)
  - Wasn't intended to output boundary data.
  - But almost always the same programming language: Fortran.

Put it all together with Argonne's Model Coupling Toolkit



MCT provides classes and methods to handle most of the routine tasks of building a parallel coupler

NSF/DOE Coupled Climate Model CCSM4/CESM1



CESM Management

- Scientific Steering Committee: Sets goals major development. Monitors progress.
- Community Advisory Board: "To provide advice to the SSC, the Director of NCAR, the NSF-ATM Program Director, and the President of UCAR on a wide spectrum of scientific and technical activities within or involving the CCSM"
- CESM Working Groups
  - Atmosphere Model; Ocean Model; Land Model; Polar Climate Biogeochemistry; Chemistry-Climate; Paleoclimate; Software Engineering; Climate Change; Climate Variability.
  - Groups meet twice a year.
  - Everyone meets at the CESM Workshop, June, Breckenridge (300-400 attendees).

www2.cesm.ucar.edu

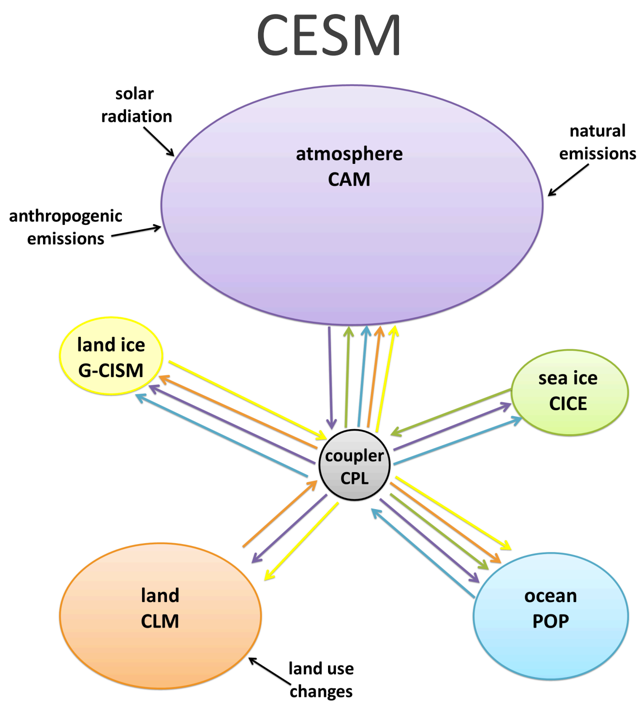
Community Earth System Model Development

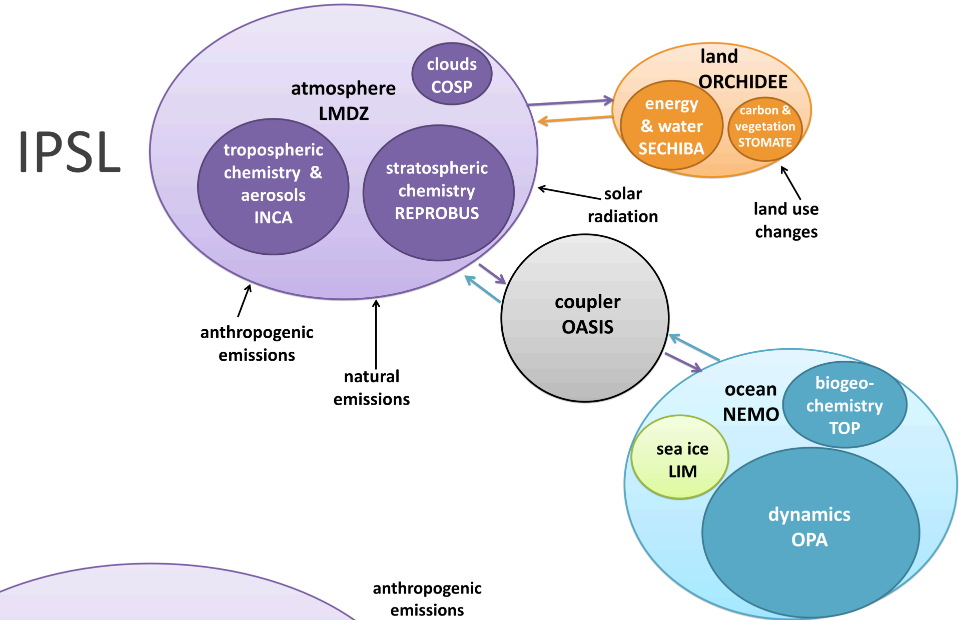
- Each sub-model has a group of expert users/developers for that discipline.

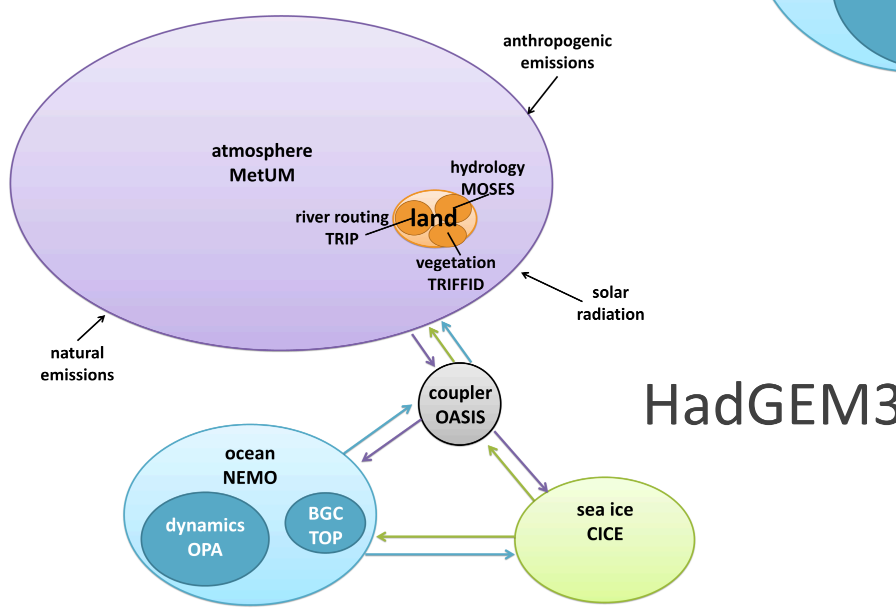
- Since the climate is created by the interaction of these systems, collaboration was required early on. First CCSM workshop was 1996.

- Introduction of new code is not formalized.
  - Typically you need to adapt to data structures already in place.
  - Informal "bakeoffs" determine which of two algorithms provides better physical simulation.
  - Working groups steered by co-chairs.
  - Working groups eventually reach consensus on new schemes.
    - Examples: New deep convection scheme, POP2, new boundary layer scheme.
  - NCAR internal CCSM Software Engineering Group makes many infrastructure decisions.

Climate model construction is similar across globe.







Figures from Kaitlin Alexander and Steve Easterbrook. Ovals proportional to code size.

Parallelism and performance

- Nearly all components are hybrid parallel (MPI and OpenMP).
  - Load balancing CESM is hard
- 100-year simulation can take weeks of wallclock time. All climate model's can write/read checkpoint (restart) files.
- Domain decomposition. Threads handle blocks of columns, several blocks per MPI task. Adjust to fit cache.
- Performance is very flat. No single kernel to optimize and gain a lot.
- Some use of GPUs: For cases with lots of tracers, puting tracer advection on GPU helps.

Validating climate models against data

The Data Problem:

- Take your coupled global climate model and calculate evolution of global weather for 100 years, 20 minutes at at a time.
  - CCSM3 (150km): 1 quadrillion operations/simulated year.

- After 100 quadrillion operations, what do you know about the climate?

NOTHING!

Climate is revealed by calculating statistics on climate model output

- Averages over time and space.
- Other moments
- More sophisticated analysis: CCA, PCA, etc.
- Compare against same calculations done with observations.

Climate model output practices

- Since running a model is very expensive AND
- Since the science comes from analyzing the output.

- Output everything!
  - Prognostic state variables
  - Derived quantities
  - Approximately 100 different variables. 25% 3D, rest 2D or 1D.

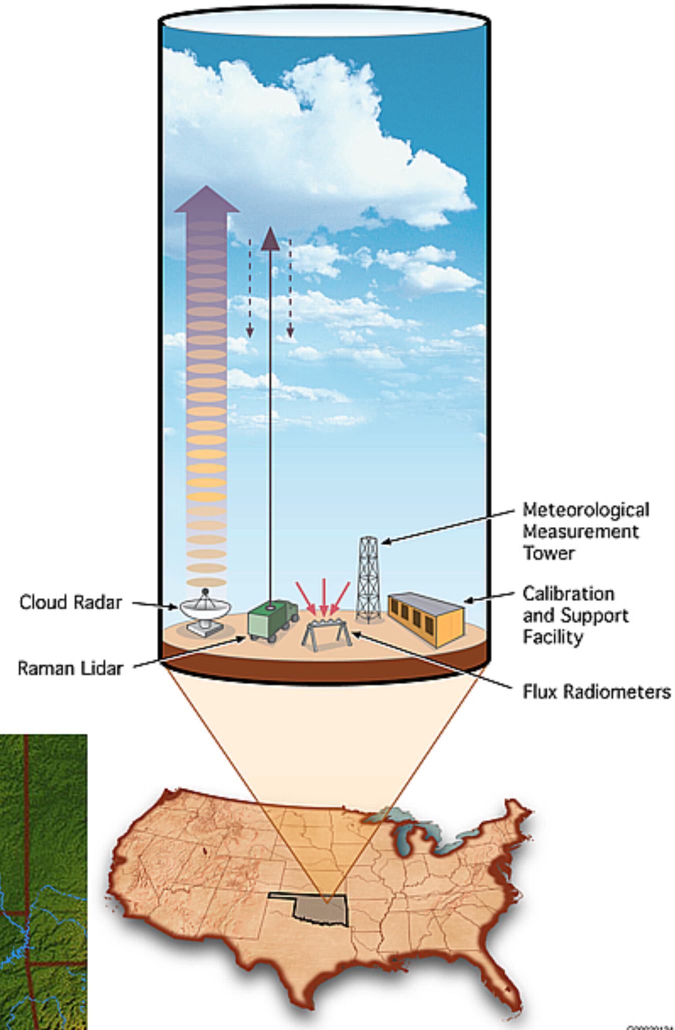
- ….But don't save everything for all times
  - Monthly output of all variables.
  - Daily or 4-hourly output of some of the same variables.

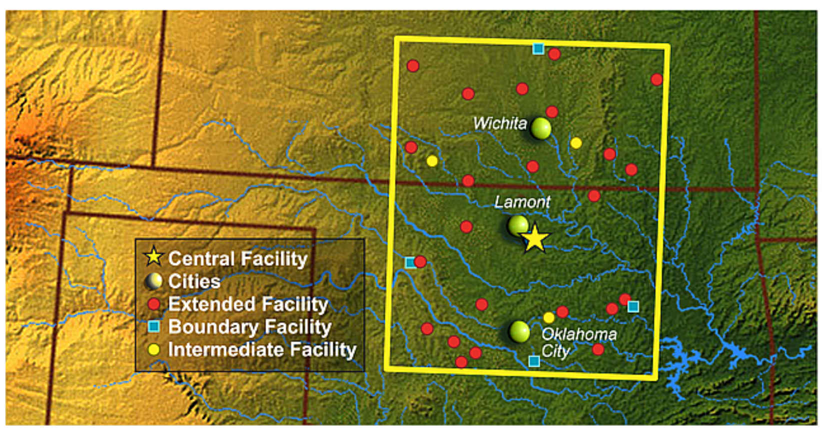
Measuring the climate is not easy!

- Should cover the whole planet from the bottom of the ocean to the top of the atmosphere
- Need to measure many variables
- Must take measurements for decades.

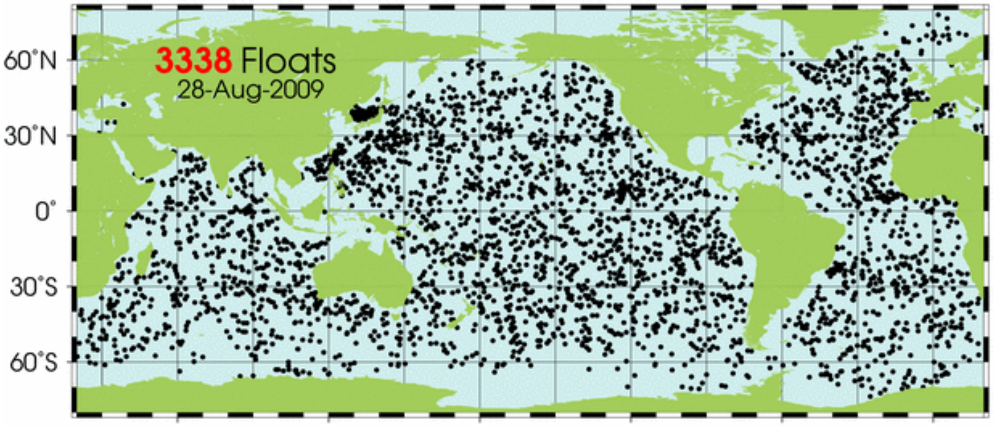
We do not come close to meeting all these goals!

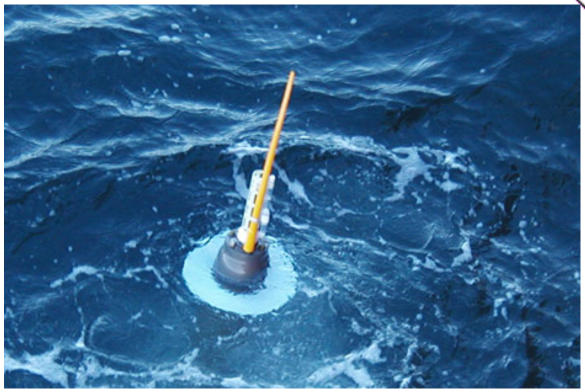
Atmospheric Radiation Measurement Program

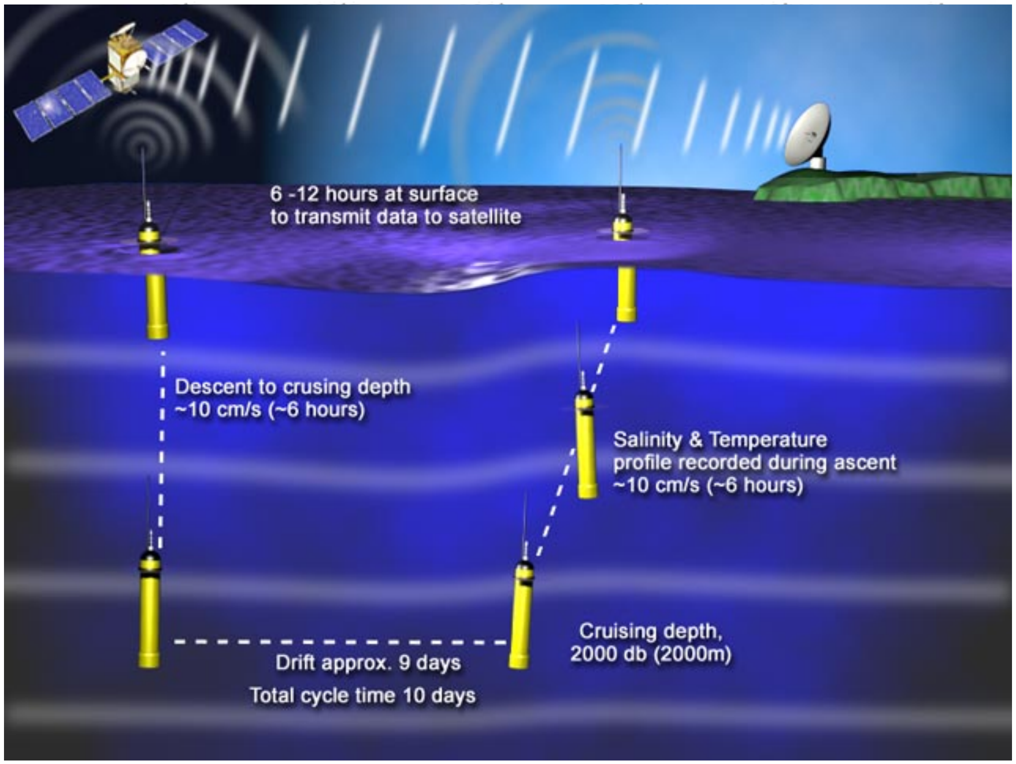


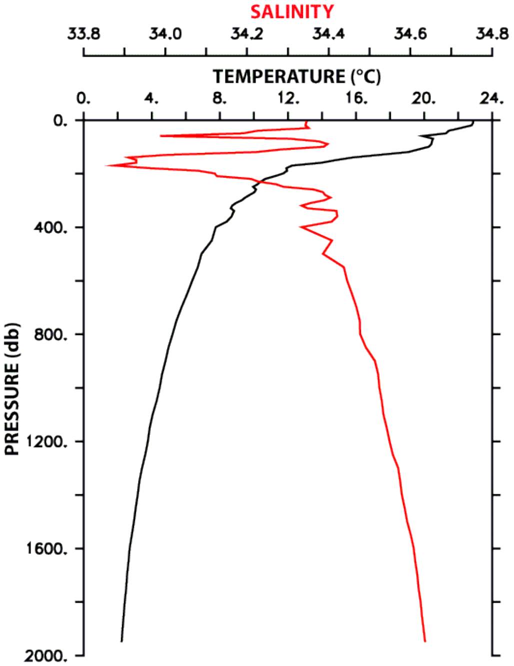


The Argo Project: Measuring the global ocean

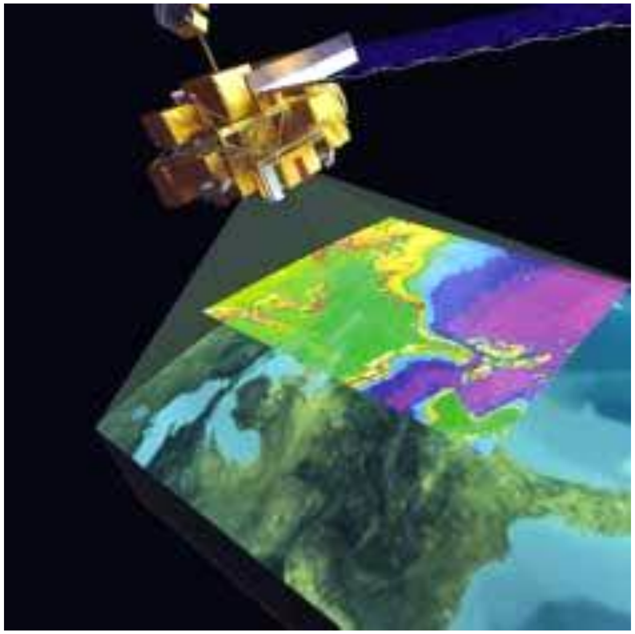


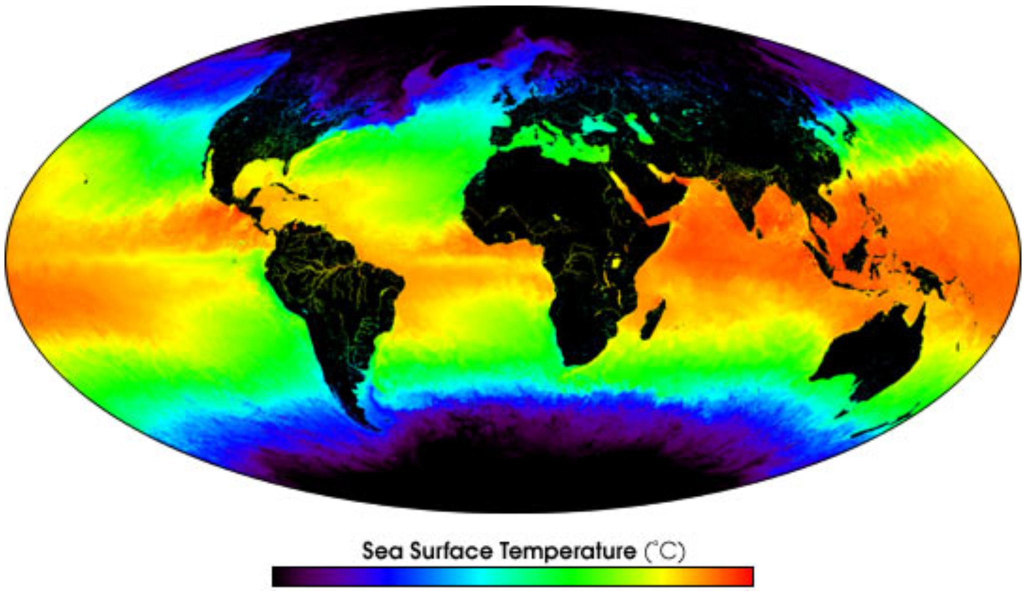


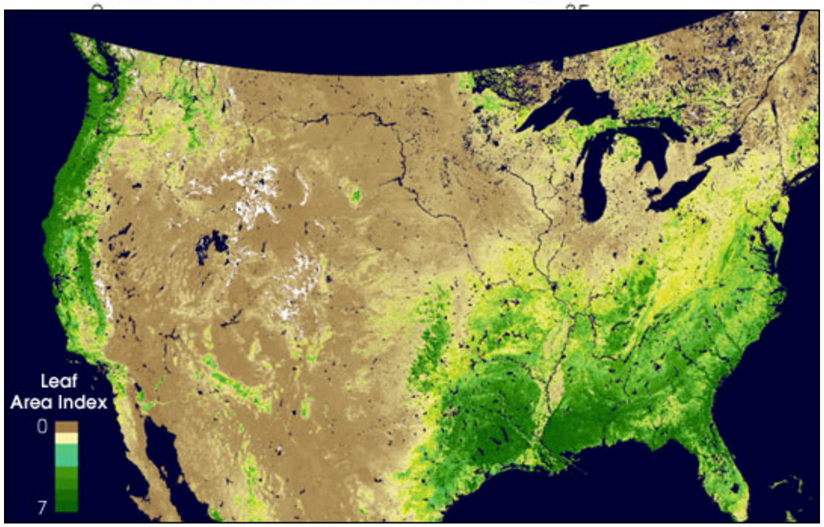




Satellites

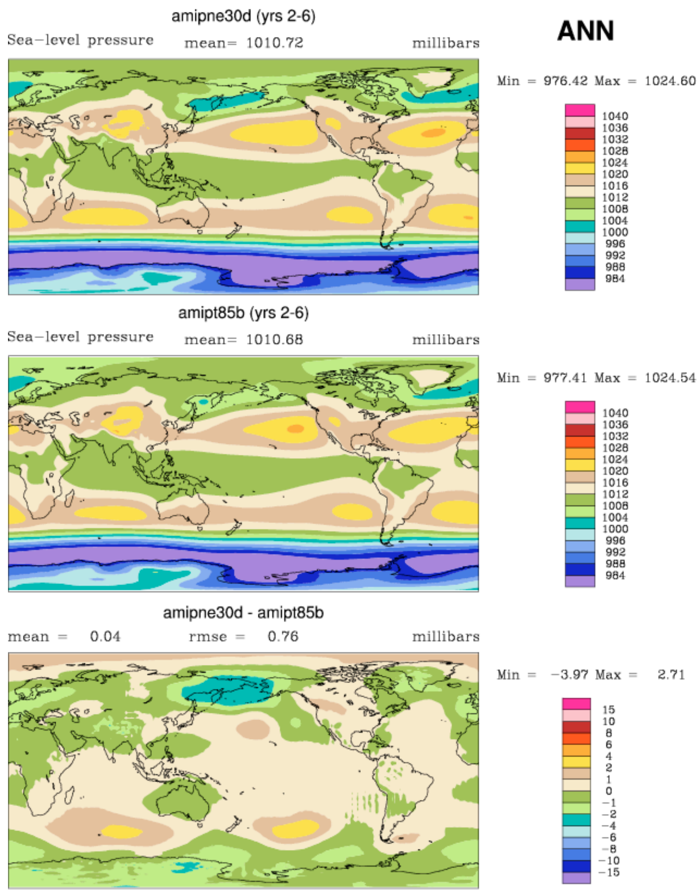


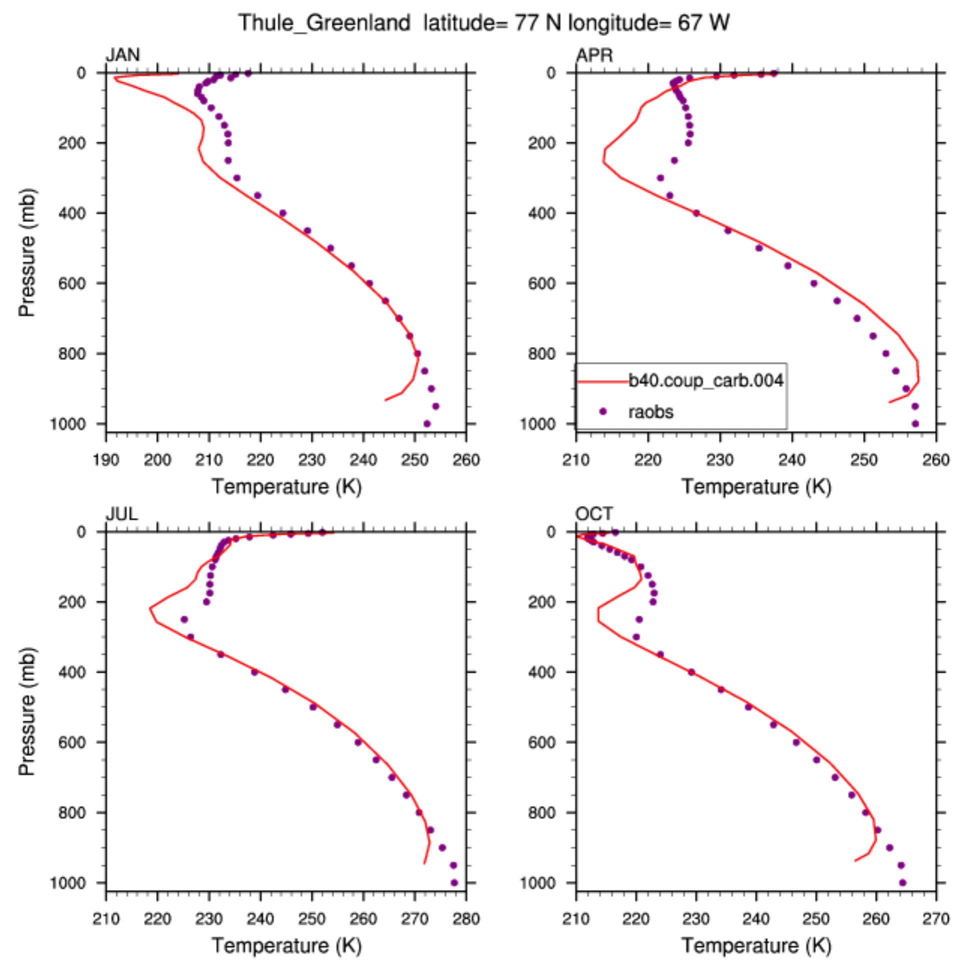




Shortcomings:
-Only a few years
-2D pictures

Insight about climate comes mostly from computationally undemanding (to plot) 2D and 1D figures.





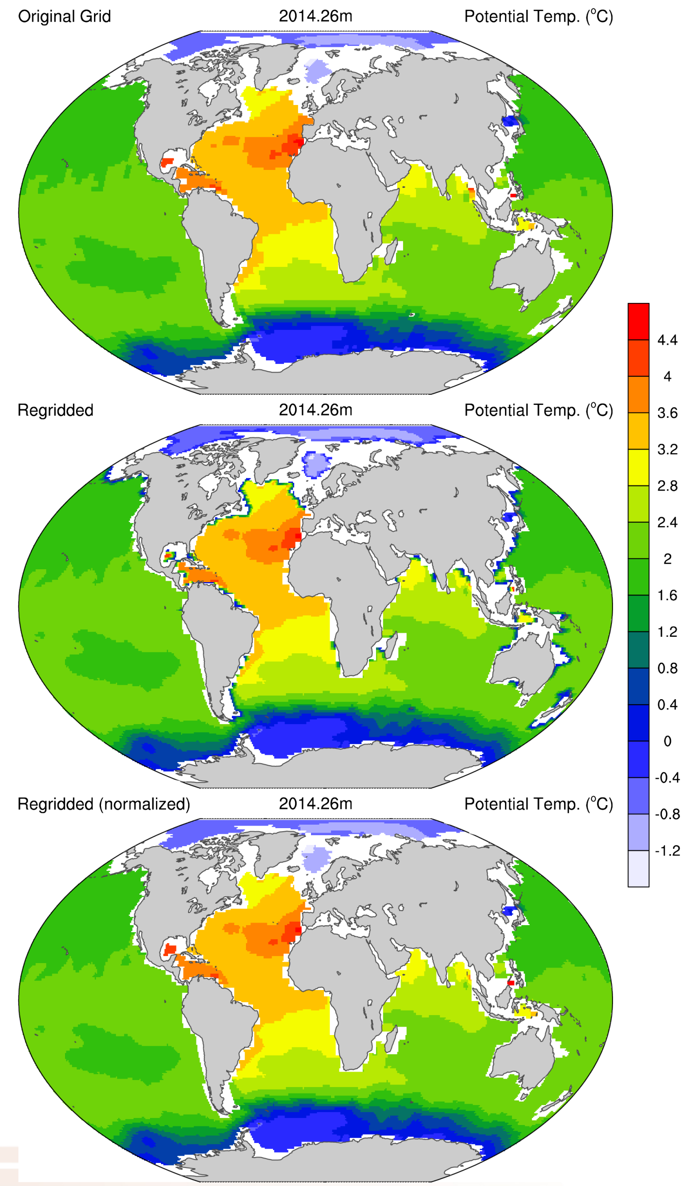
Why? The atmosphere and ocean have a small aspect ratio; 10,000 km vs. 10 km.

NCAR Command Language (NCL)

A scripting language tailored for the analysis and visualization of geoscientific data

1. Simple, robust file input and output
2. Hundreds of analysis (computational) functions
3. Visualizations (2D) are publication quality and highly customizable

- **Community-based tool**
- Widely used by CESM developers/ users
- UNIX binaries & source available, free
- Extensive website, **regular workshops**



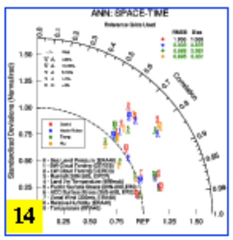
http://www.ncl.ucar.edu/

AMWG Diagnostics

Set Description

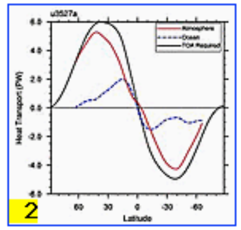
1 Tables of ANN, DJF, JJA, global and regional means and RMSE.
2 Line plots of annual implied northward transports.
3 Line plots of DJF, JJA and ANN zonal means
4 Vertical contour plots of DJF, JJA and ANN zonal means
4a Vertical (XZ) contour plots of DJF, JJA and ANN meridional means
5 Horizontal contour plots of DJF, JJA and ANN means
6 Horizontal vector plots of DJF, JJA and ANN means
7 Polar contour and vector plots of DJF, JJA and ANN means
8 Annual cycle contour plots of zonal means
9 Horizontal contour plots of DJF-JJA differences
10 Annual cycle line plots of global means
11 Pacific annual cycle, Scatter plot plots
12 Vertical profile plots from 17 selected stations
13 Cloud simulators plots
14 Taylor Diagram plots
15 Annual Cycle at Select Stations plots

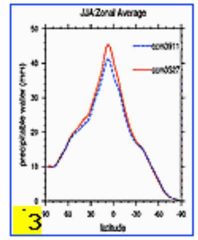
TABLES

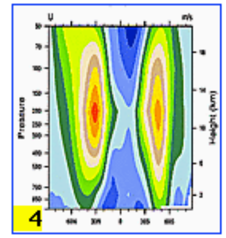


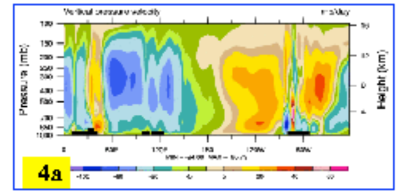
METRICS

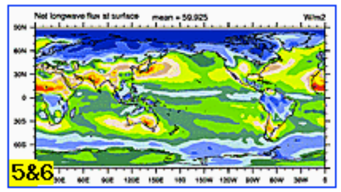
Click on Plot Type

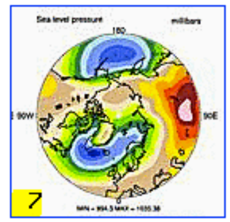


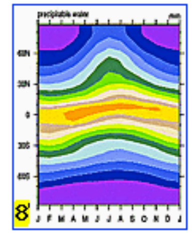


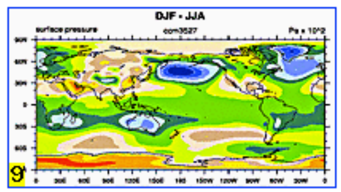


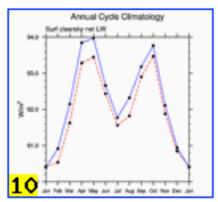


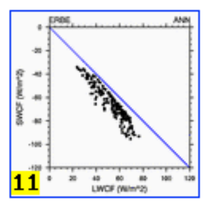


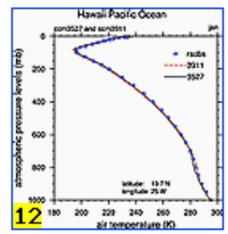


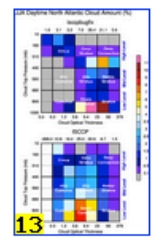


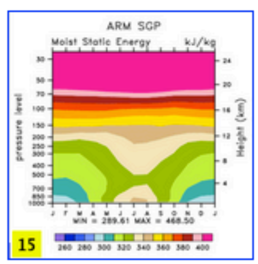




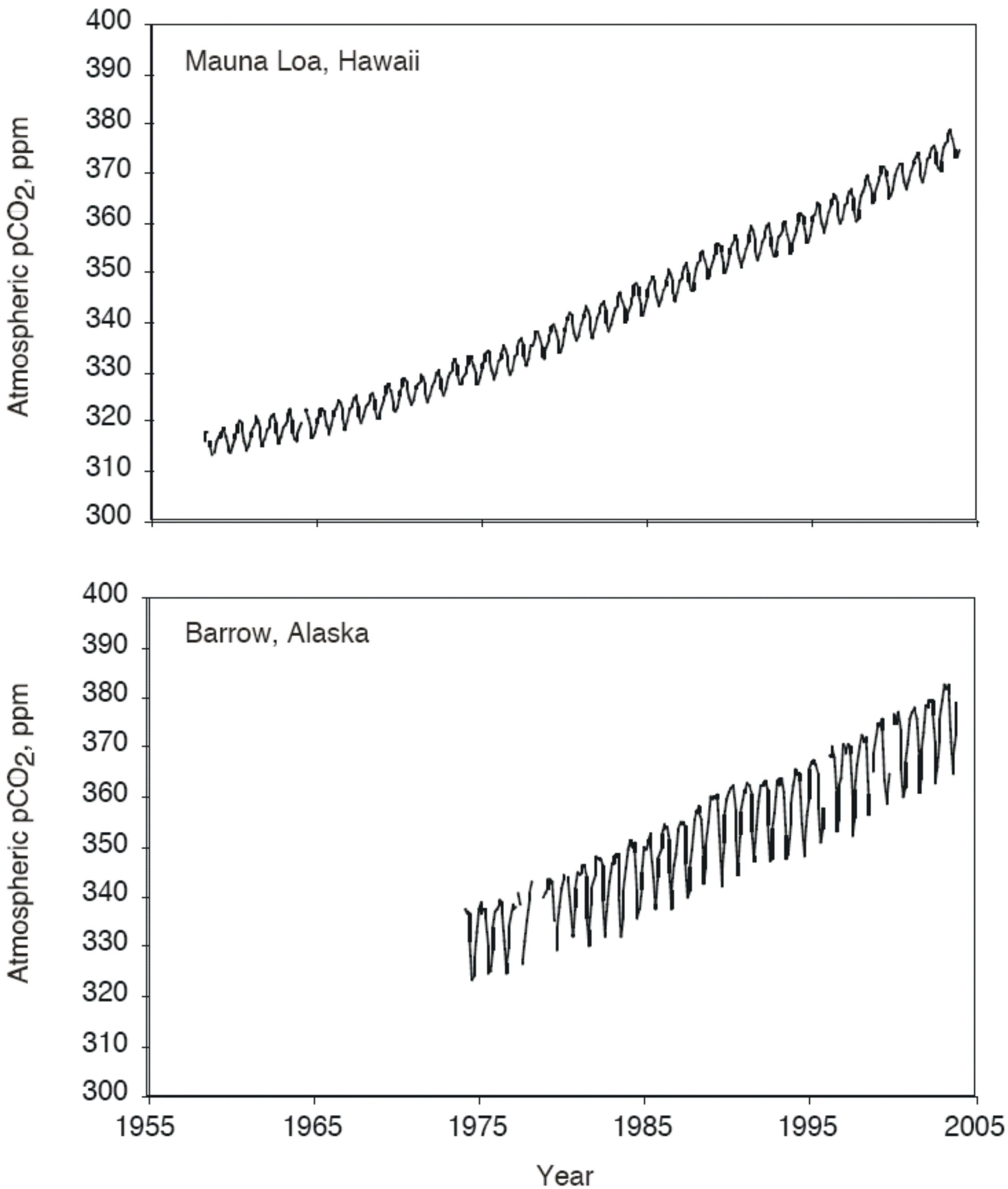






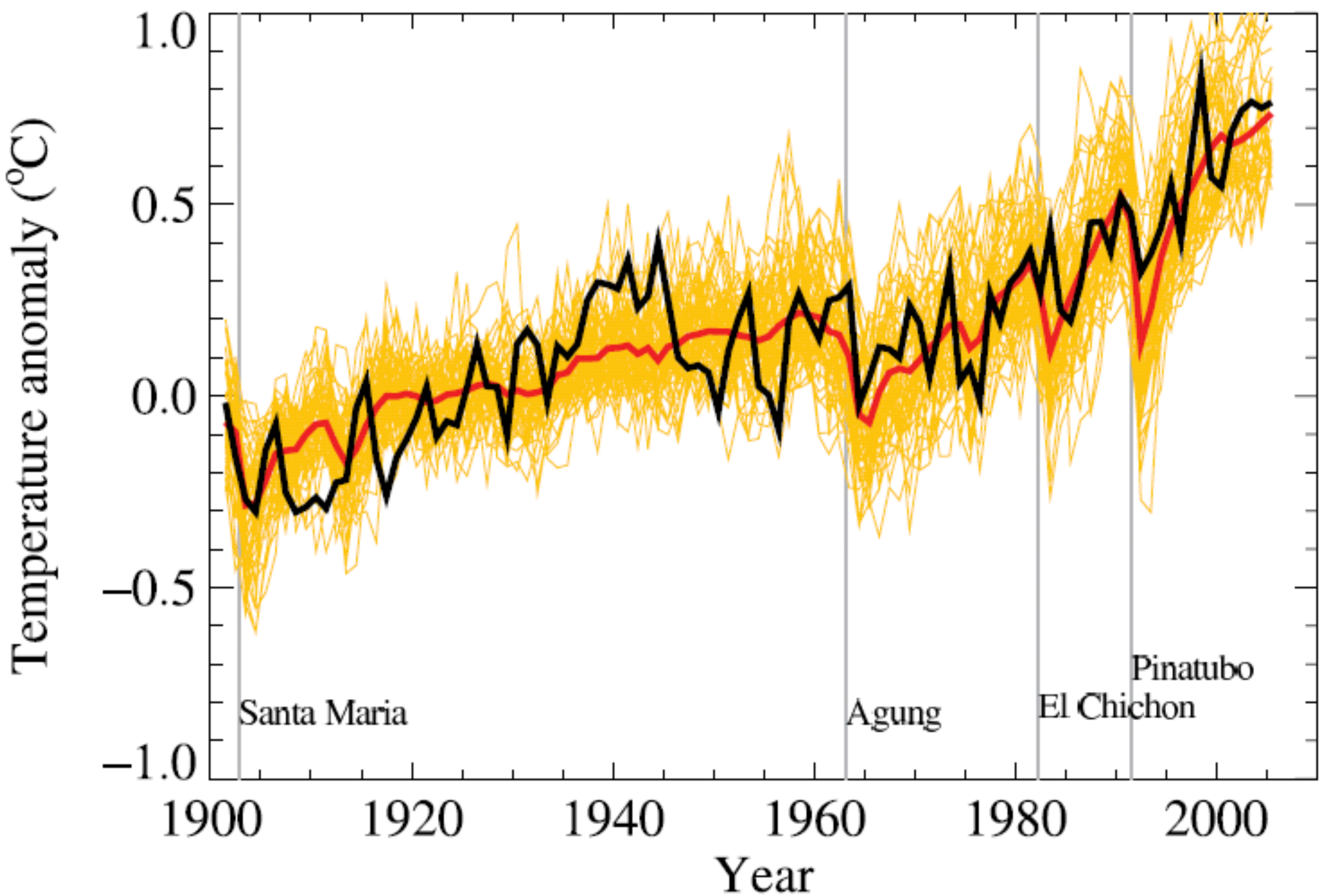


Climate Model Applications

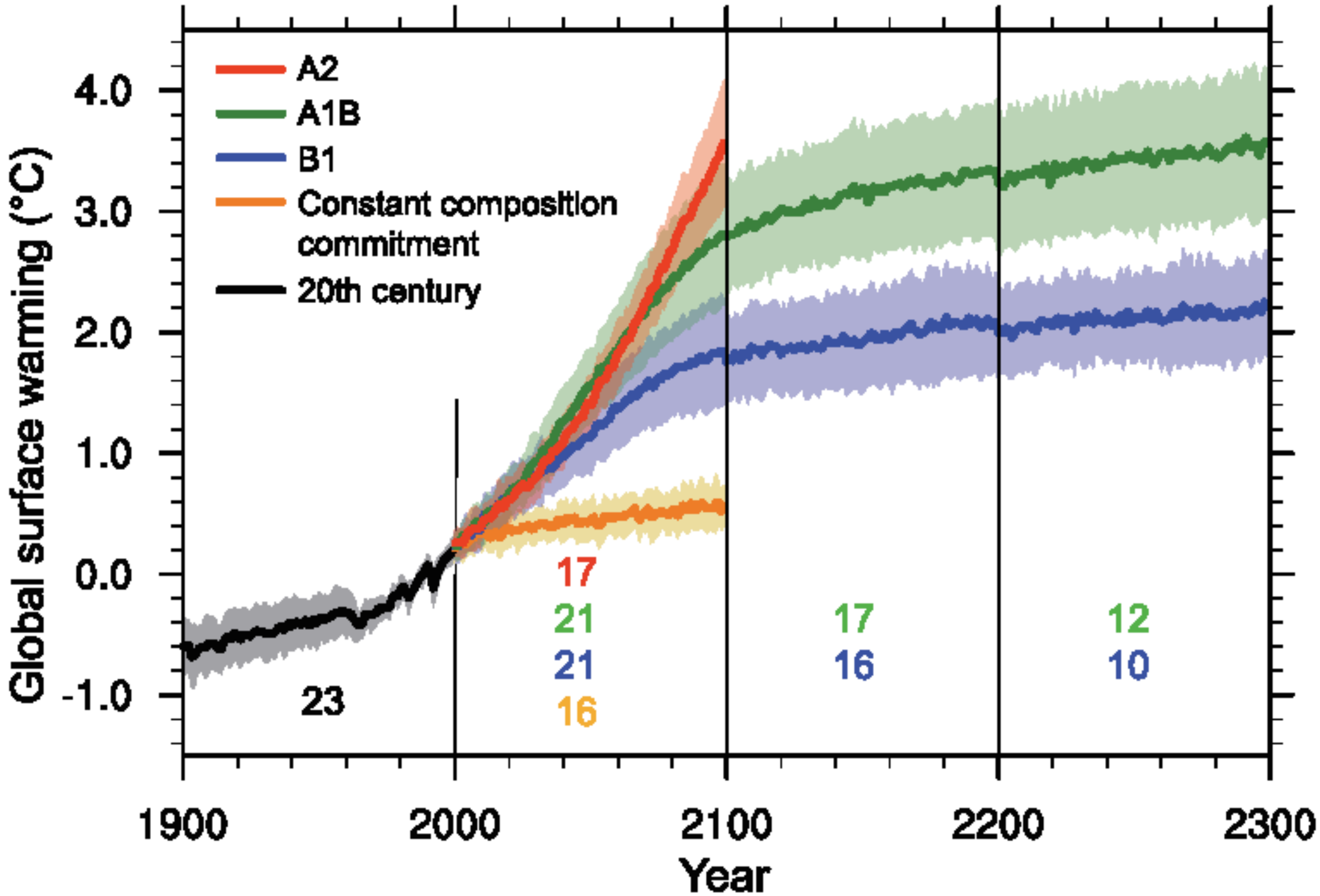


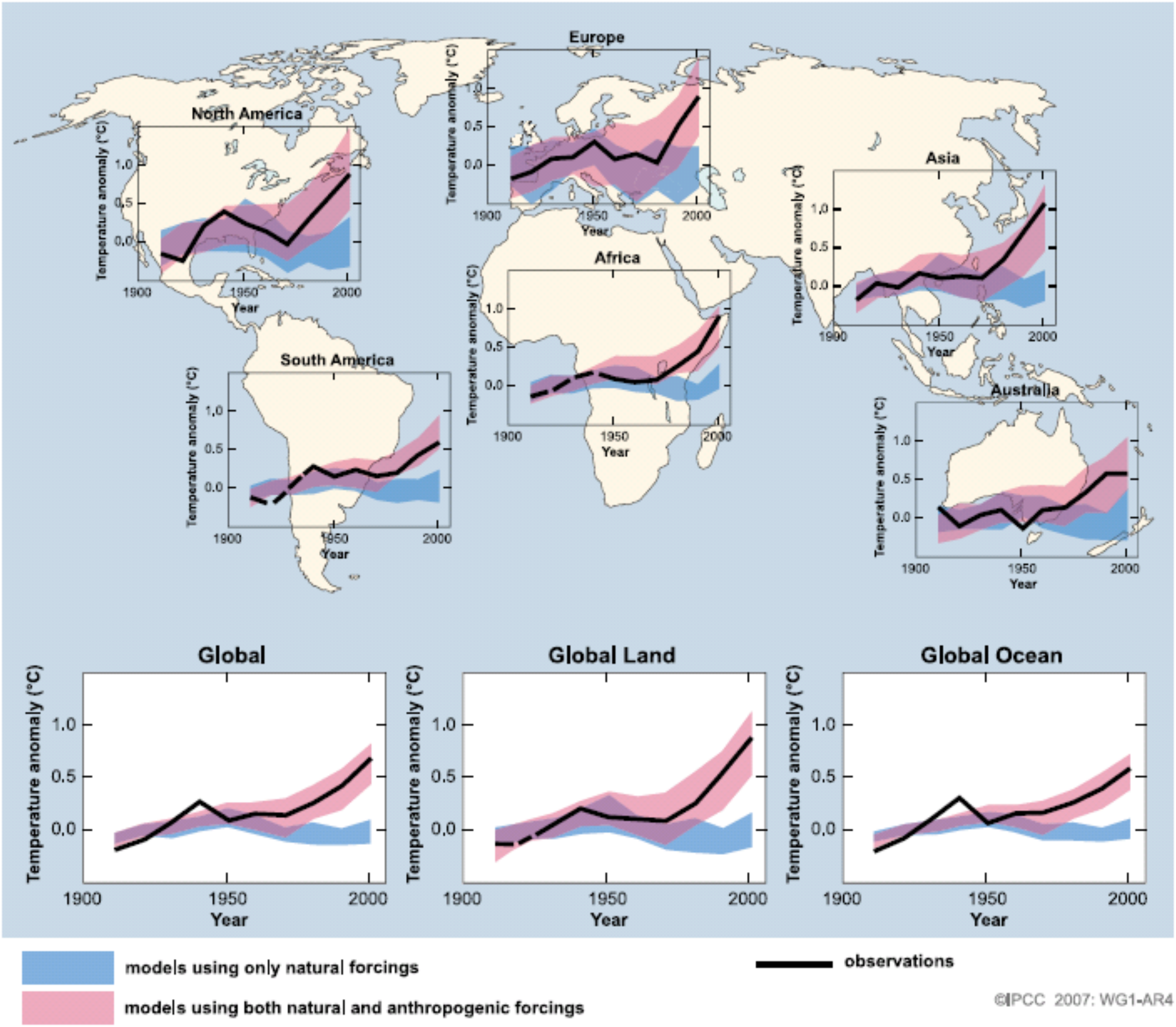
The main application of climate models: climate change

Multi-model simulations of the 20th Century (IPCC AR4)



Climate Prediction with CO2 increase (IPCC AR4)

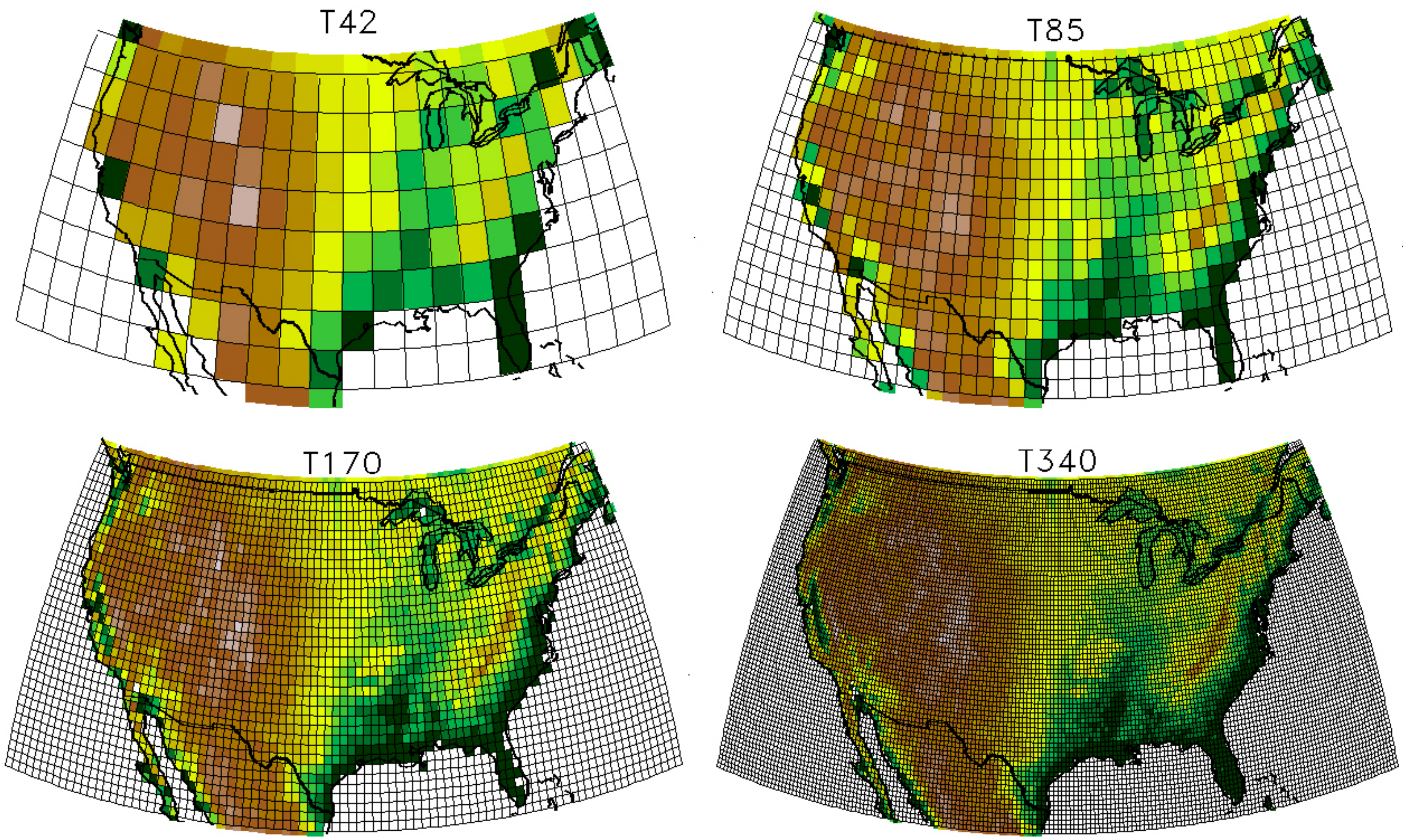




Europe
North America
Asia
Africa
South America
Australia
Global
Global Land
Global Ocean
Temperature anomaly (°C)
1.0
0.5
0.0
1900
1950
2000
Year
models using only natural forcings
models using both natural and anthropogenic forcings
observations
©IPCC 2007: WG1-AR4

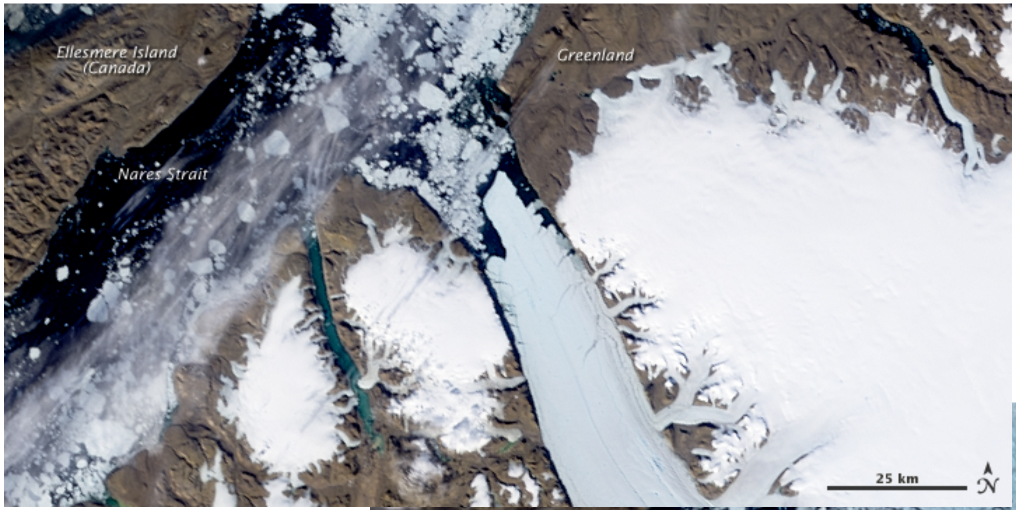
Future Considerations

Resolving regional details about climate change requires higher resolution (necessary but not sufficient).



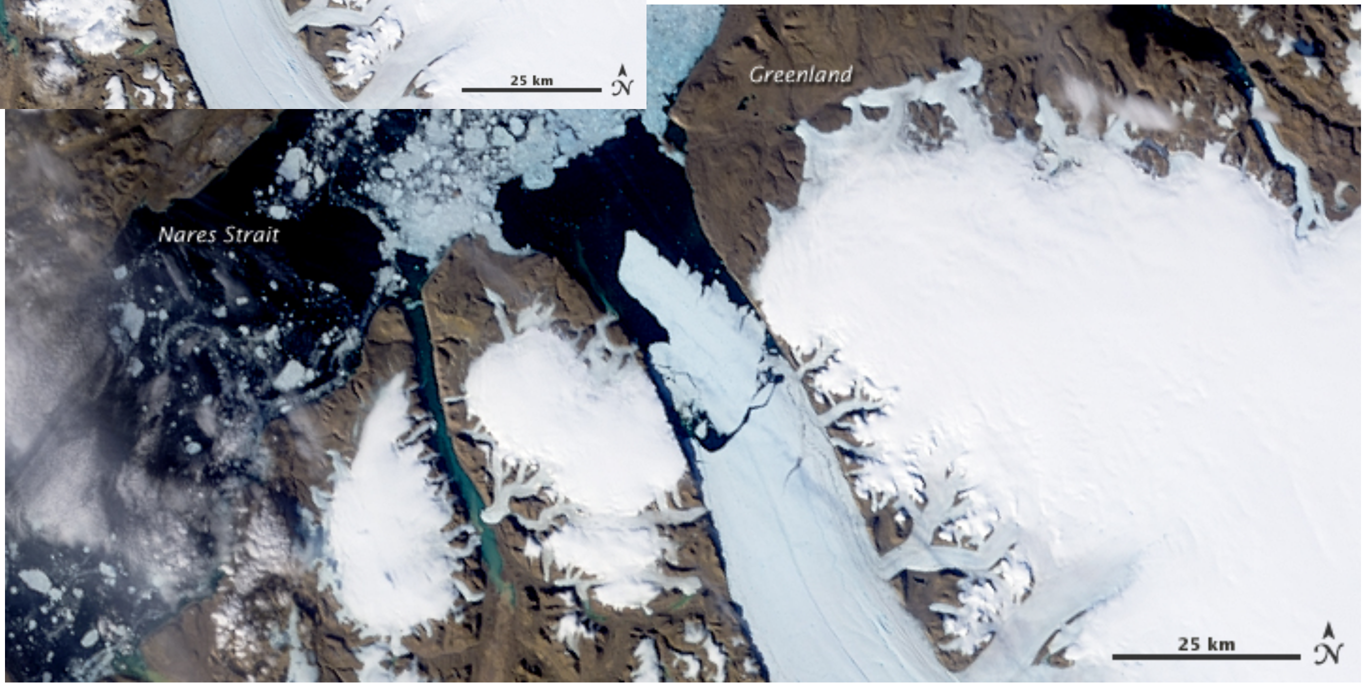
Regional effects are important for key parts of the system.

July 28, 2010

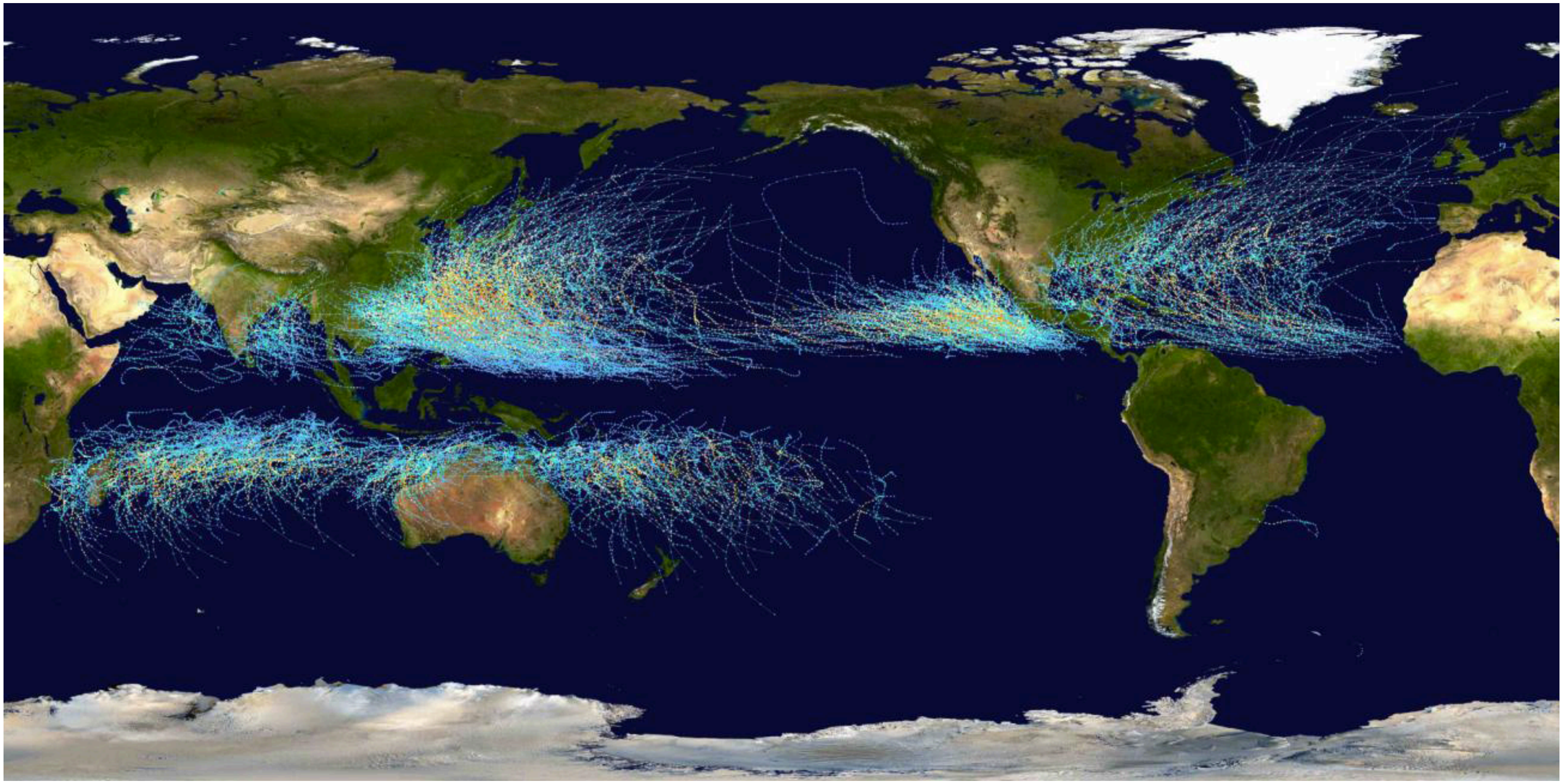


Peterman Glacier, Greenland

August 5, 2010

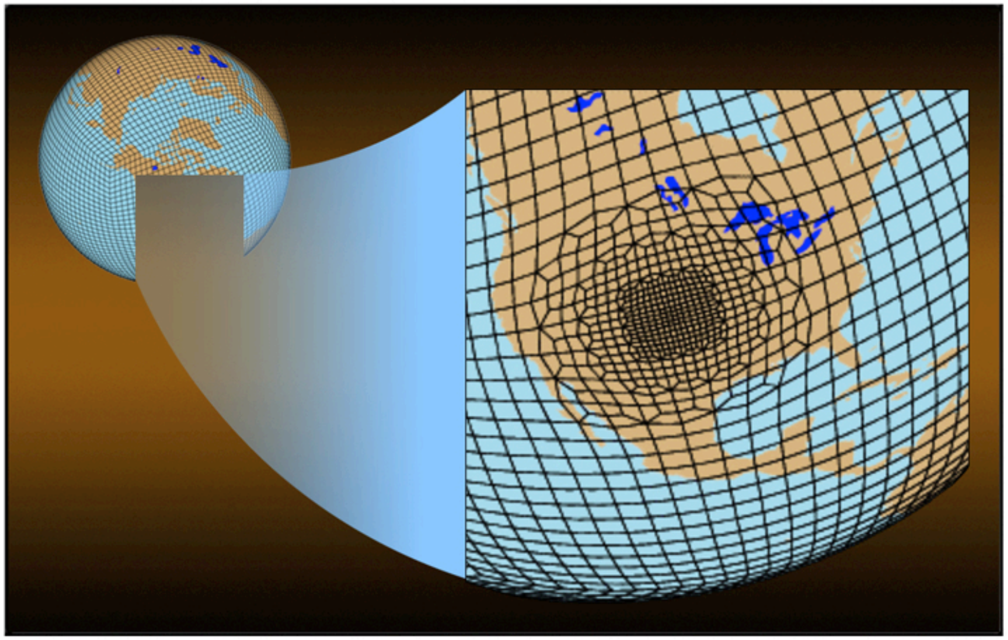


Need high resolution for hurricanes - a vital part of the climate system.

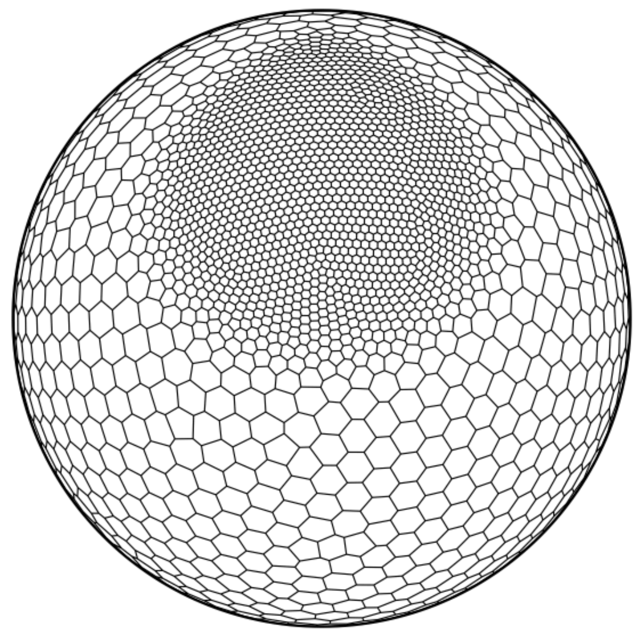


All tropical cyclone tracks 1985-2005. Tracks colored by max wind speed from weak (blue) to red (strong)

One Path to higher Resolution: Regionally refined grids



Same dynamics throughout



ACME: Accelerated Climate Model for Energy

Goal: Focus DOE modeling activities to develop a high resolution Earth System Model (ESM) that effectively utilizes DOE expertise and computers and supports DOE mission and science. Code for a slightly smaller community.

Branch from the Community Earth System Model beginning in 2014 to develop an advanced version made available back to the community by 2017.

Primary science focus - Ultra-high resolution 80 year simulations:

- **1970-2010 hindcast with automat evaluation and calibration against observations (like CSSEF project)**
- **2010-2050 projection, with uncertainty characterization.**

For next 20-40 years, climate change is expected to be mostly independent of scenario, with change determined by system inertia ("change in the pipeline")